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AN INVESTIGATION OF THE TOWING CHARACTERISTICS OF THE DEEP SUBMERGENCE RESCUE VEHICLE. PART I. SUBMERGED TOWING IN CALM WATER

Charles W. Sieber, et al

Naval Ship Research and Development Center
Bethesda, Maryland

March 1974

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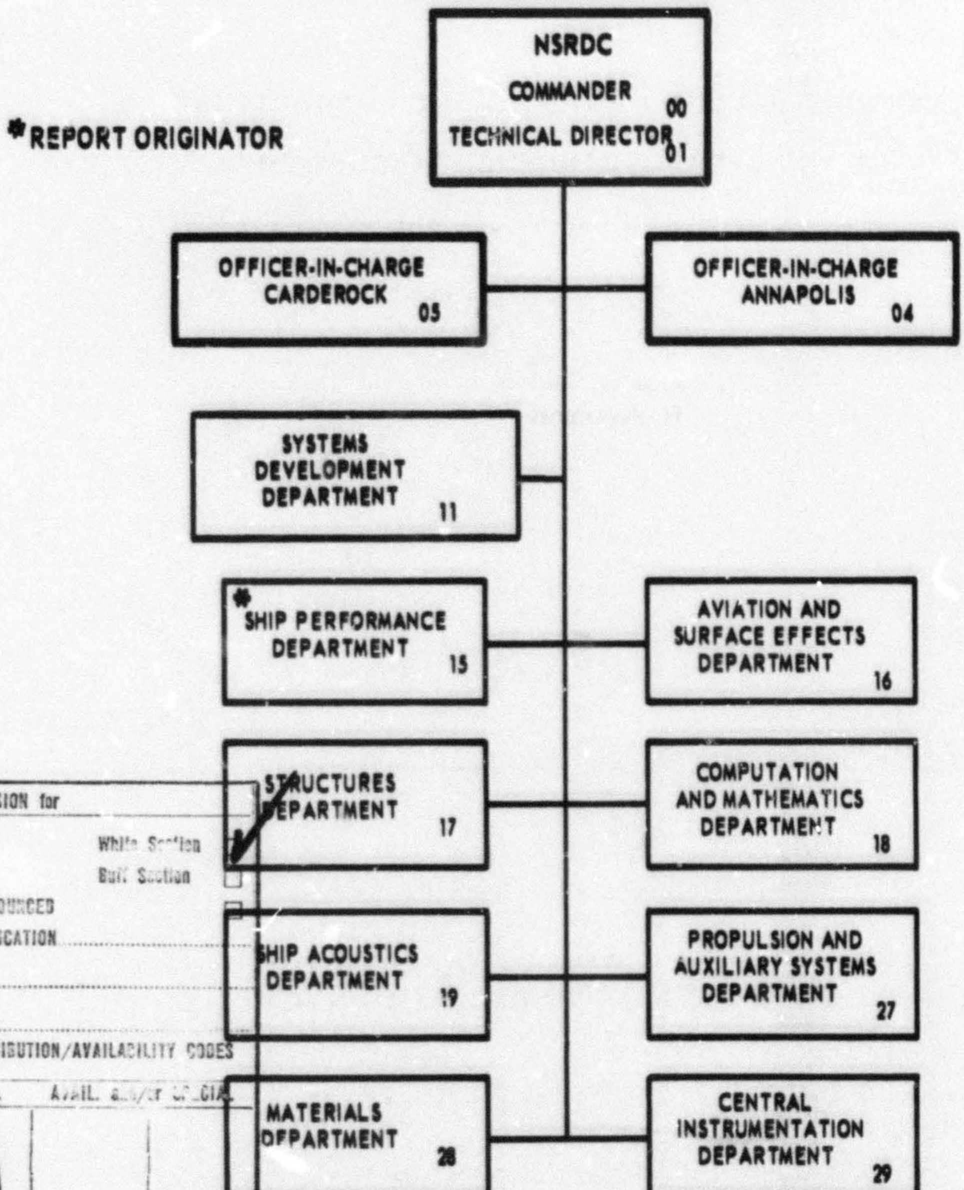

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The submerged towing characteristics of the Deep Submergence Rescue Vehicle (DSRV) are examined for a variety of towpoints and ballast conditions. The results indicate that DSRV can be readily towed at speeds up to at least 15 knots from towpoints located on the forward hard ring with vehicle net buoyancies from 0–2000 pounds positive. The hydrodynamic downforce produced by the vehicle without additional appendages such as a depressor is sufficient to produce towing depths of 100–150 feet with less than 500 feet of submerged towline length.

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AN INVESTIGATION OF THE TOWING CHARACTERISTICS OF THE DEEP SUBMERGENCE RESCUE VEHICLE
PART 1 – SUBMERGED TOWING IN CALM WATER

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NOTATION

A_n	Amplitude of n th oscillation
B	Total buoyancy of the hull envelope
F_n	Froude number, $V/\sqrt{gL}$
g	Local acceleration of gravity
I_x	Real moment of inertia in roll
I_y	Real moment of inertia in pitch
K	Rolling moment
$K_{\dot{p}}$	Added hydrodynamic moment of inertia in roll
L	Characteristic length
$M_{\dot{q}}$	Added hydrodynamic moment of inertia in pitch
T_θ	Natural period of oscillation in pitch
T_ϕ	Natural period of oscillation in roll
V	Velocity
W	Total weight including entrained water
Z_B	Vertical location of the centroid of the hull envelope
Z_G	Vertical location of the center of total mass
δ	Damping ratio, $\ell_n (A_{n+1}/A_n)/2\pi$
θ	Angle of pitch
π	Linear scale ratio
ρ_m	Fluid density for model
ρ_p	Fluid density for prototype
ϕ	Angle of roll
ϕ_0	Towline angle at the vehicle
ψ	Angle of yaw

ABSTRACT

The submerged towing characteristics of the Deep Submergence Rescue Vehicle (DSRV) are examined for a variety of towpoints and ballast conditions. The results indicate that DSRV can be readily towed at speeds up to at least 15 knots from towpoints located on the forward hard ring with vehicle net buoyancies from 0–2000 pounds positive. The hydrodynamic downforce produced by the vehicle without additional appendages such as a depressor is sufficient to produce towing depths of 100–150 feet with less than 500 feet of submerged towline length.

ADMINISTRATIVE INFORMATION

This research was funded by the Naval Ship Systems Command under Naval Ship Engineering Center Work Request WR-1-6120 of 21 January 1971 and Naval Ship Systems Command Project Order PO 1-0269 of 28 June 1971, Naval Ship Research and Development Center Work Unit 1548-704.

INTRODUCTION

At the request of the Naval Ship Systems Command, the Naval Ship Research and Development Center (NSRDC) undertook a program to develop a contingency technique for towing the Deep Submergence Rescue Vehicle (DSRV) at high speed with a ship-of-opportunity. The DSRV is a small air-transportable submersible primarily designed to rescue personnel from a disabled submarine and transfer them to another submarine or to the surface. It is envisioned that circumstances might arise in which a specialized support ship would not be immediately available, making it necessary to employ a more or less unequipped ship-of-opportunity to tow the vehicle to the rescue site.

This report deals strictly with submerged towing performance in calm water. A primarily experimental approach was used in the investigations. For most experimentation, an existing large scale model was used to minimize viscous effects between model and full-scale. Some additional towing was done with a smaller model to check towing stability with longer towlines and several ballast conditions. Also, predictions of steady towing attitudes and forces for a wide variety of ballast conditions were made utilizing data previously obtained with the larger scale model. Basic operational considerations for accomplishing a tow are discussed; the prototype, the models, the associated test equipment and instrumentation, and

the procedures that were used in the experimental towing investigations are described; and the results of these investigations, including data for both steady-state conditions and transient behavior, are presented. Finally, predicted towing configurations using long towline lengths are presented.

OPERATIONAL CONSIDERATIONS AND RESTRICTIONS

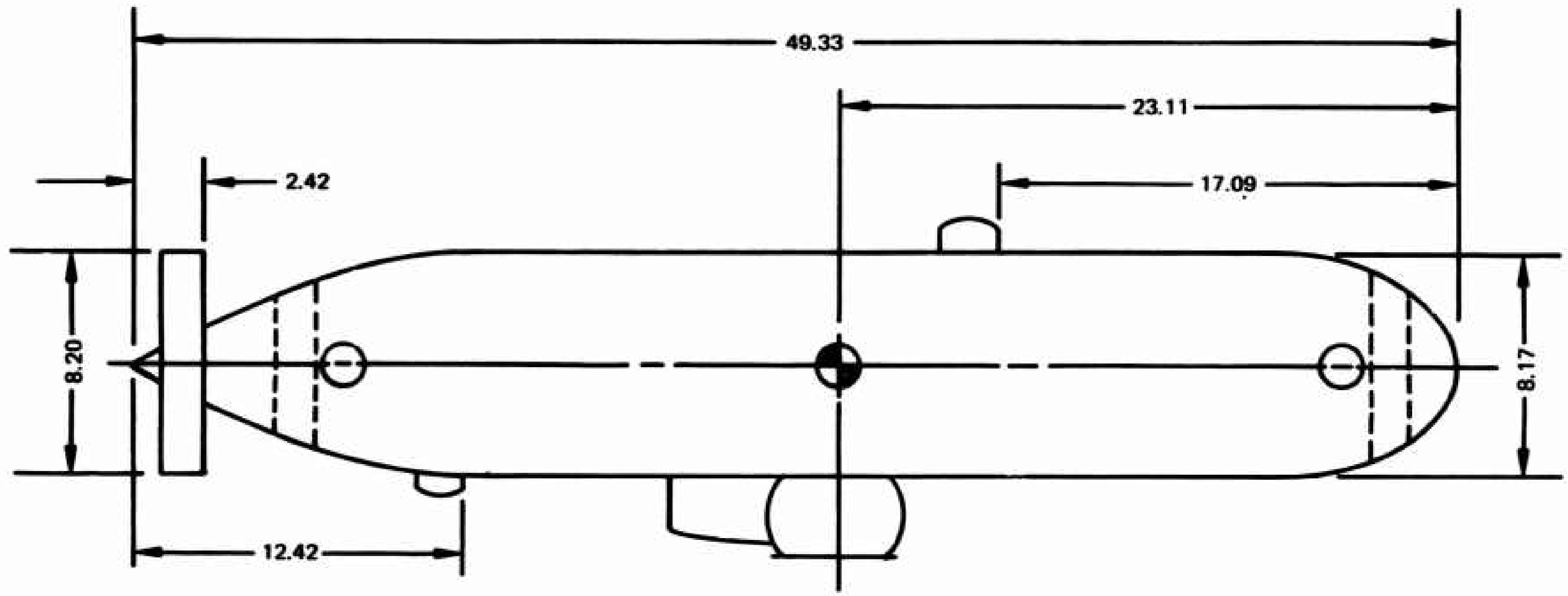
There were several basic operational considerations and restrictions imposed in the development of towing techniques. These are as follows:

1. The outer envelope of the DSRV is constructed of formed glass-reinforced plastic and is intended only for streamlining purposes. Any towing loads must be taken by two circumferential rings located fore and aft on the vehicle. The vehicle can be towed only from the existing light-alloy fittings protruding through the skin from these rings.
2. The towline(s) should not come in contact with the envelope due to the fragile nature of the glass-reinforced plastic.
3. In the interest of safety, the vehicle should be positively buoyant.
4. For simplicity and reliability, the use of additional bodies such as depressors, auxiliary surfaces, or appendages on the vehicle should be avoided.
5. The propeller should be freewheeling.
6. The shroud must be fixed in place, preferably at zero deflection so that the tow can be accomplished without a crew.

DESCRIPTION OF PROTOTYPE AND MODELS

The overall configuration of the prototype vehicle as represented for this investigation is shown by sketch in Figure 1. The basic hull is a body of revolution 49.33 feet in length and 8.17 feet in maximum diameter. The hull envelope contains forward and aft sets of vertical and horizontal thrusters which provide control for low-speed maneuvering. At the stern is an all-movable control shroud and a three-bladed propeller for main propulsion. External to the envelope are the transfer skirt assembly (consisting of a mating skirt, a shock mitigation system, and a splitter plate) located below the hull and two small fairings which house electronic components.

The vehicle is represented for experimentation by two models with different scale ratios. The first is NSRDC Model 5128, a 16.44-foot-long, free-flooding, mahogany model



ALL DIMENSIONS ARE IN FEET

Figure 1 – DSRV Hull Geometry Showing Principal Full-Scale Dimensions

geometrically scaled from the prototype with a linear ratio of 3. Propellers in the thruster ducts are omitted. This model with minor modifications for towing is shown in Figures 2–4. The second model, designated NSRDC Model 5200, is a 2.32-foot-long mahogany model with a linear scale ratio of 21.28. Propellers are omitted, from the thruster ducts in this model as well. Model 5200 is shown in Figures 5–7.

Detailed geometrical characteristics of the prototype and the models are presented in Table 1.

MODEL PREPARATIONS

The following modifications and preparations were performed on the models.

MODEL 5128

1. The splitter plate behind the mating skirt was altered to a length corresponding to that currently fitted to the prototype.
2. A servo mechanism was fitted to the tail to permit deflections of the shroud in the horizontal plane from a remote station on the towing carriage. Details of this installation are shown in Figures 8 and 9. (In this report, for deflections in the horizontal plane, the shroud will be referred to as the "rudder".)
3. The vertical position of the shroud was locked at an angle of incidence of 0 degrees.
4. The model was fitted with towpoints at several positions forward. At the station of the forward hard ring (located approximately 12 feet aft of the forward perpendicular on the prototype), towpoints were installed at locations corresponding to the lifting eyes, the ASR capture arms, and the trapeze hooks. Of these towpoints, only those corresponding to the lifting eyes and the capture arms were employed, but two intermediate sets of towpoints were located in effect by means of short-legged nylon bridles. Figure 10 details the effective locations of all towpoints used and a typically installed towpoint is shown in Figure 11. Considerable internal structure was added to withstand the loads expected on the various towpoints.

MODEL 5200

1. The model was converted to a free-flooding condition to facilitate frequent and rapid changes in ballast.
2. A free-wheeling stern propeller which approximated the prototype propeller was installed.
3. Towpoints were installed at locations corresponding to the forward lifting eyes and the forward ASR capture arms.

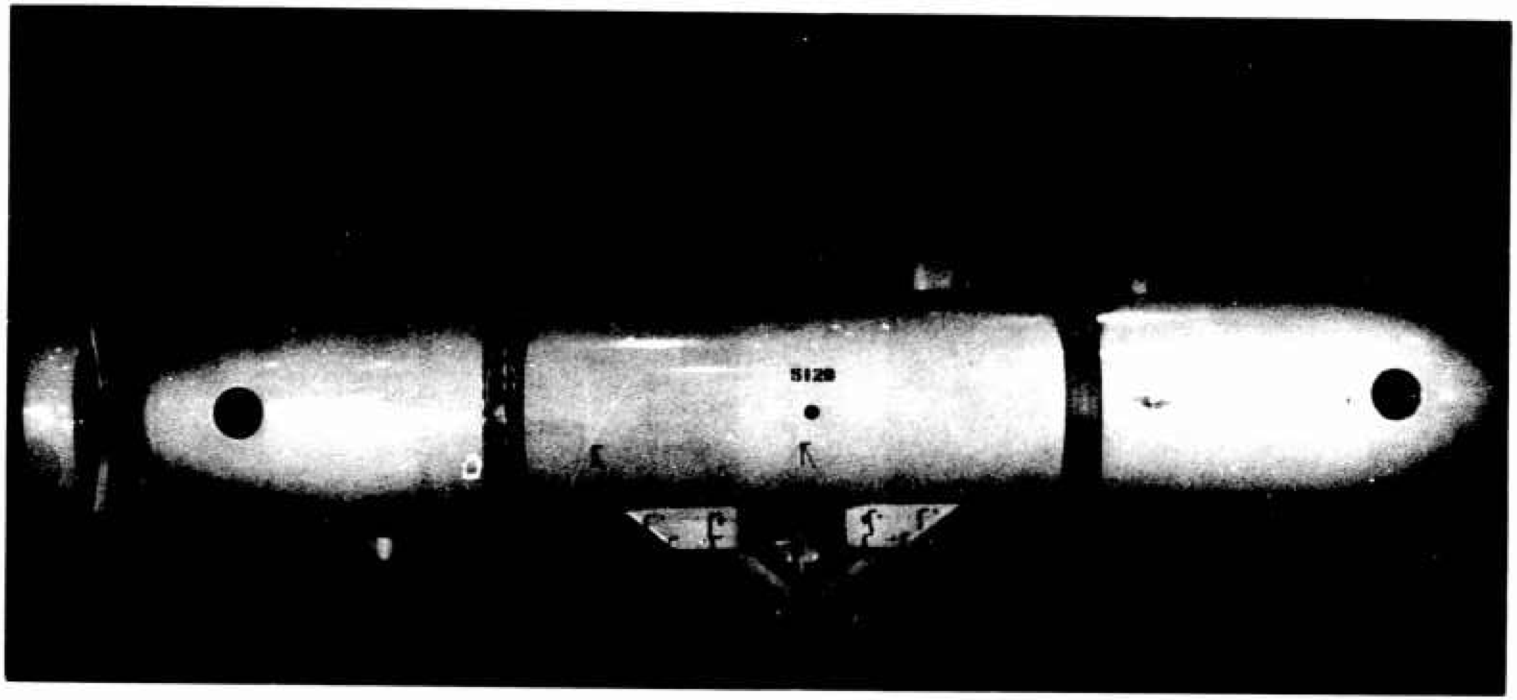


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Figure 2 – Profile View of DSRV Model 5128

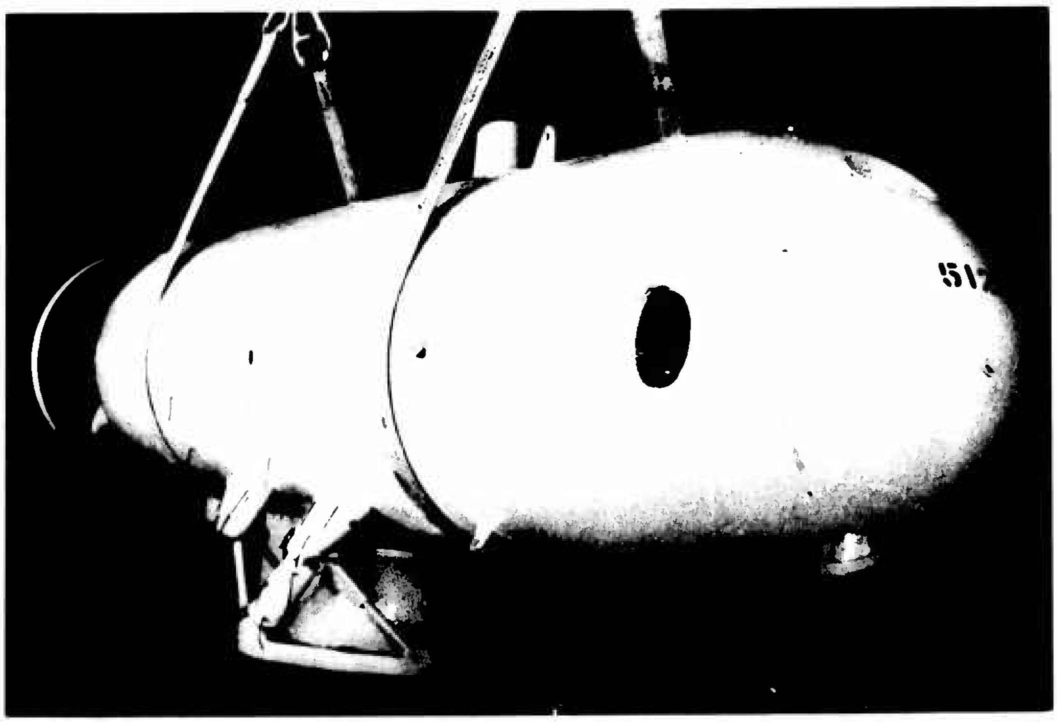

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Figure 3 – Starboard Bow View of DSRV Model 5128

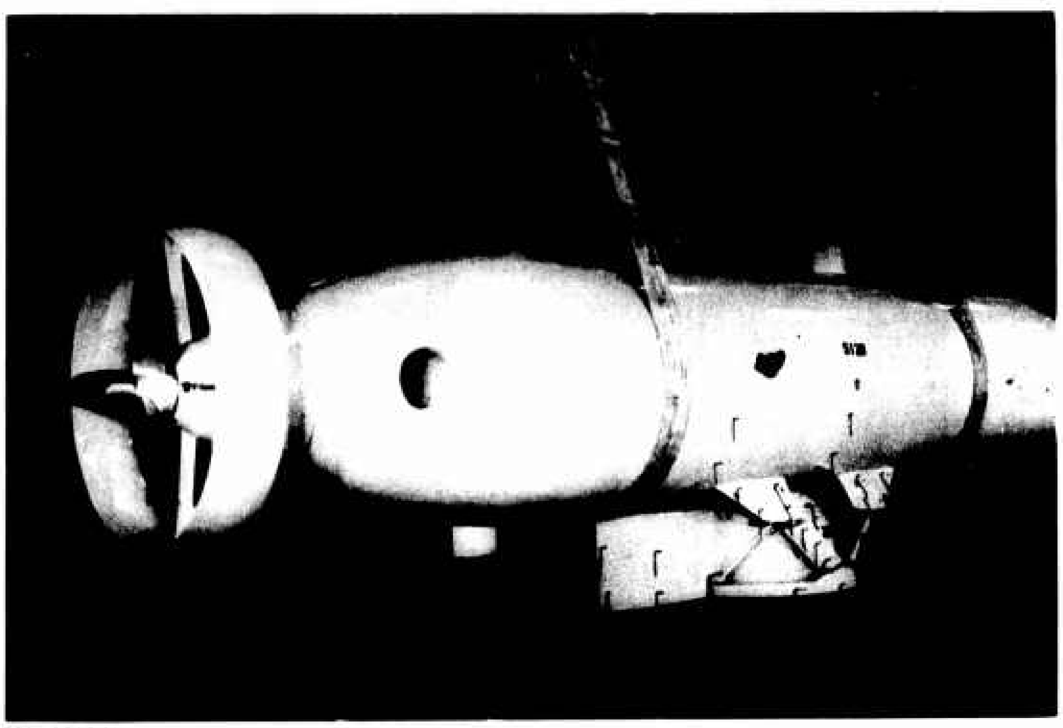

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Figure 4 – Starboard Quarter View of DSRV Model 5128

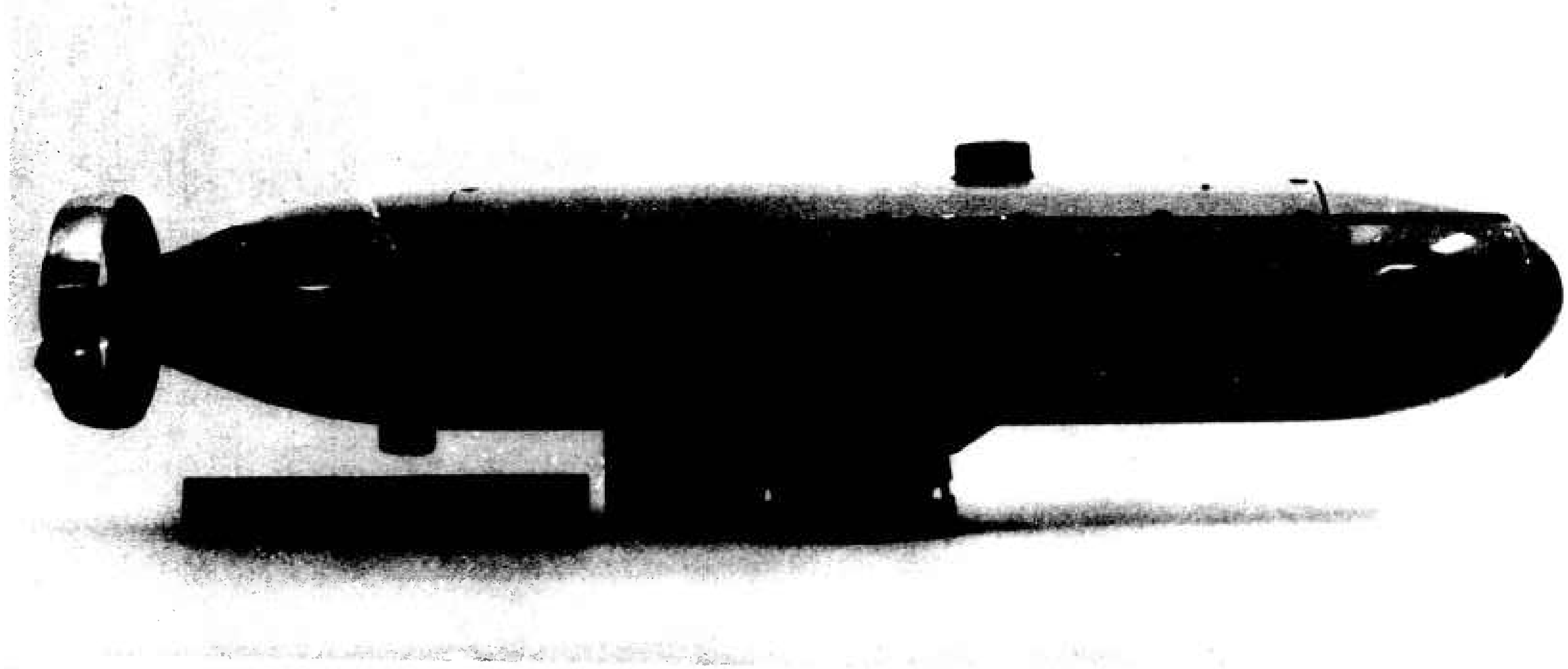

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Figure 5 – Profile View of DSRV Model 5200

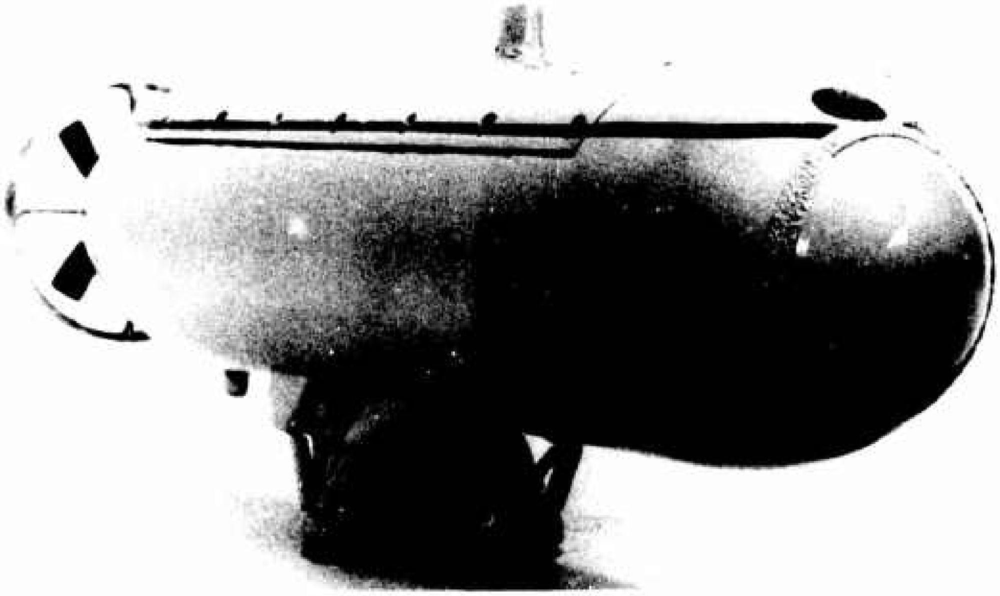

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Figure 6 – Starboard Bow View of DSRV Model 5200

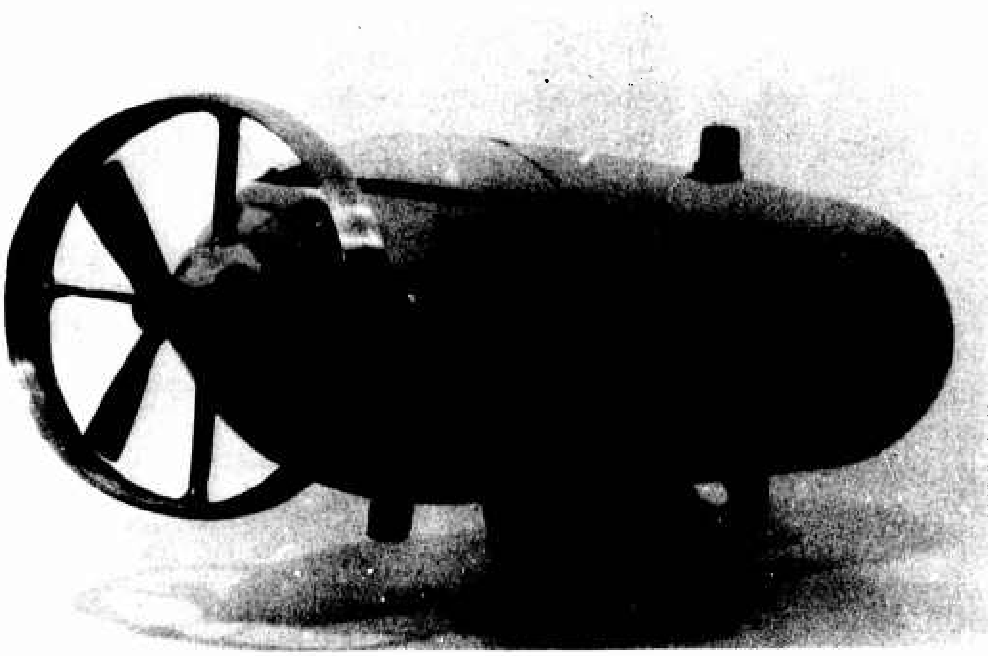

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Figure 7 – Starboard Quarter View of DSRV Model 5200

TABLE 1 GEOMETRIC CHARACTERISTICS OF THE DSRV PROTOTYPE AND MODELS

	Prototype	Model 5128	Model 5200
General Characteristics			
Linear Scale Ratio	1.00	3.00	21.28
Overall Length, feet	49.33	16.44	2.32
Maximum Beam, feet	8.17	2.72	0.38
Wetted Surface Area, square feet	1318.2	146.46	2.91
Volume of Hull Envelope, cubic feet	2184.5	80.91	0.27
Longitudinal Distance to Centroid of Hull Envelope from Forward Perpendicular, feet	23.11	7.70	1.09
Height of Centroid of Hull Envelope Above Baseline, feet	3.92	1.30	0.18
Stern Shroud			
Maximum Diameter, feet	8.20	2.73	0.39
Section Chord, feet	1.83	0.61	0.09
Planform Area, square feet	14.62	1.62	0.03
Aspect Ratio	4.33	4.33	4.33
Section Chord Angle, degrees	3.5	3.5	3.5
NACA Section Profile (minus 8.33 percent at trailing edge)	0015	0015	0015
Longitudinal Distance to Leading Edge from Aft Perpendicular, feet	2.42	0.81	0.11
Stern Propeller		Model 4280	
Diameter, feet	6.00	2.00	0.28
Number of Blades	3	3	3
Blade Rake Angle, degrees	17.72	17.72	0
Pitch Ratio at 0.7 Radius	0.93	0.93	0.40

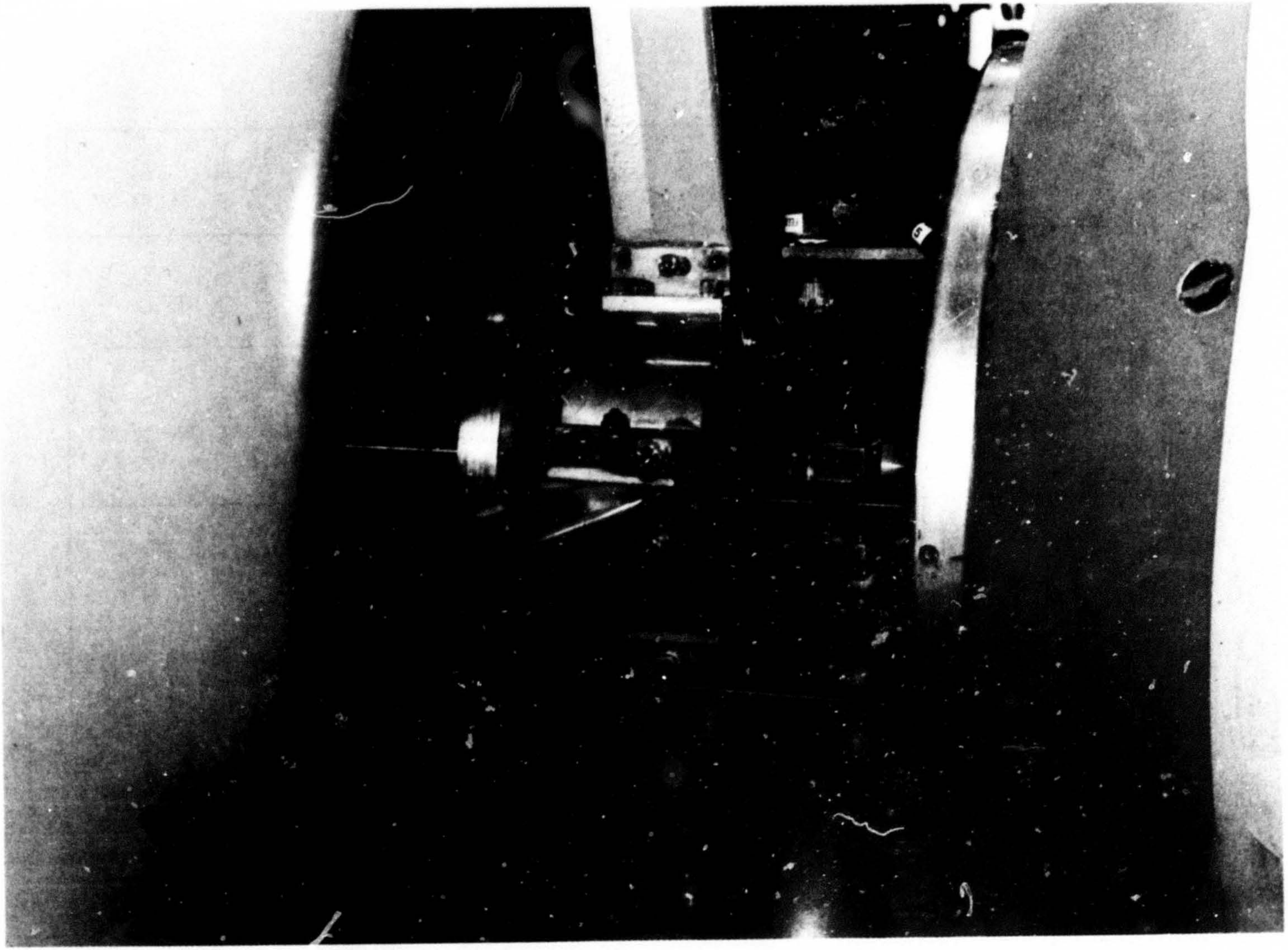

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Figure 8 – Side View of Shroud Servo Mechanism

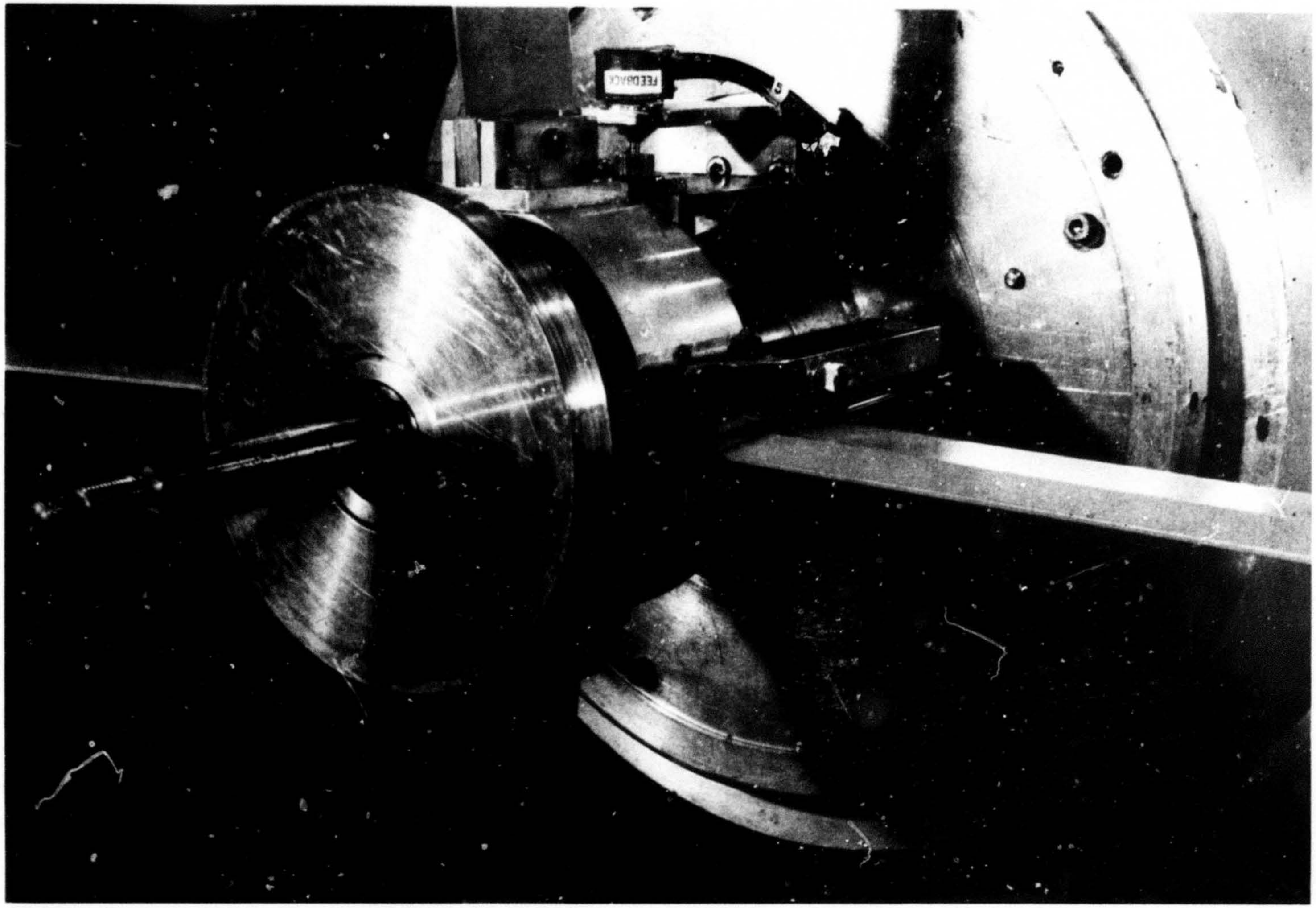

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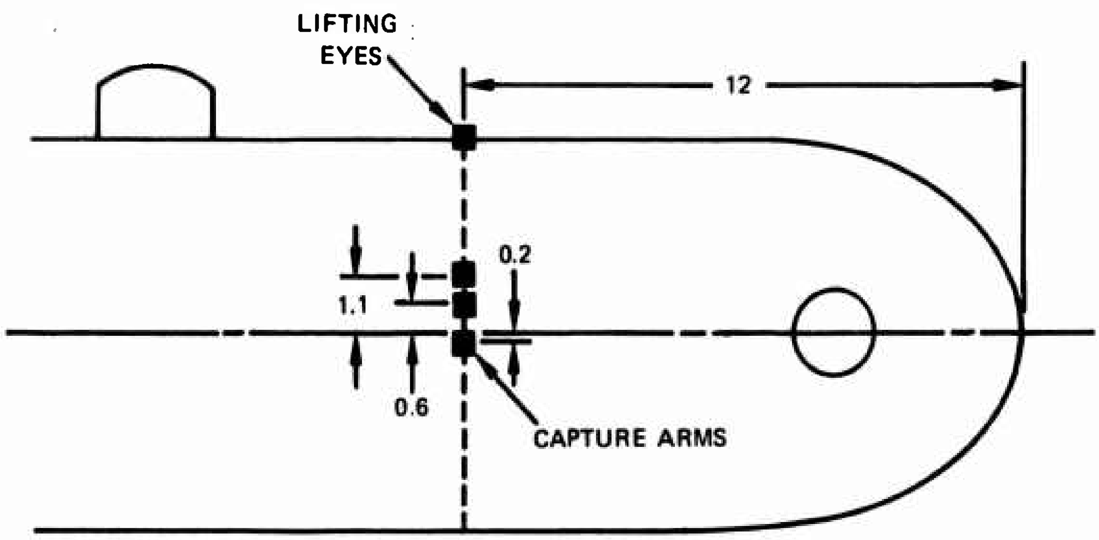
Figure 9 – Quarter View of Shroud Servo Mechanism



ALL DIMENSIONS ARE IN FEET

Figure 10 – Side View Showing Effective Full-Scale Locations of the Towpoints on the Forward Hard Ring

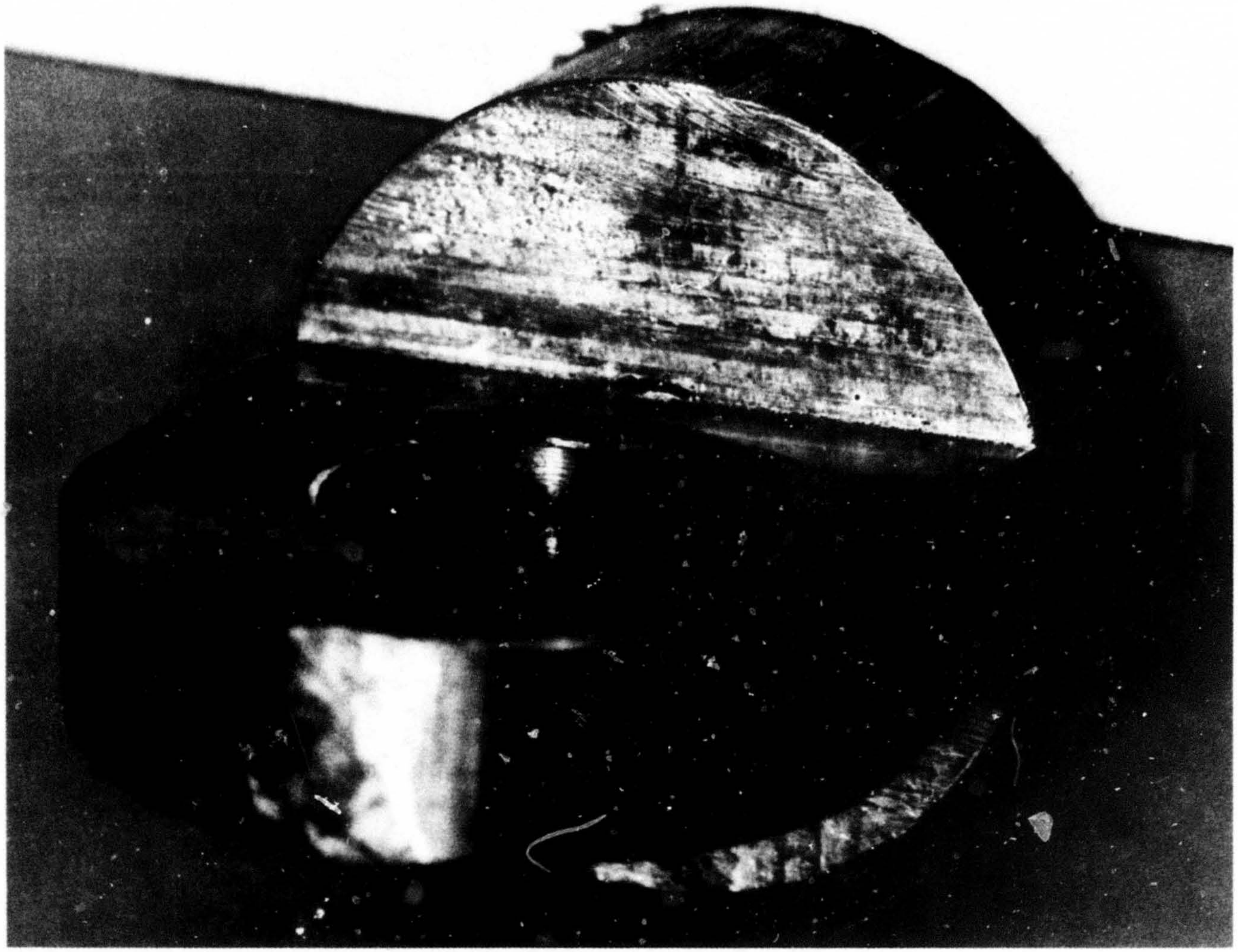


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Figure 11 – Detailed View of Typical Model 5128 Towpoint Fitting

4. A sand strip to stimulate boundary layer turbulence was installed around the nose of the body at a station corresponding to the location of the sand strip on Model 5128 and 2.0 feet aft of the forward perpendicular on the prototype.

MODEL BALLASTING PROCEDURES

The ballasting procedures, all of which were conducted with the models flooded and fully submerged in water, are outlined below:

MODEL 5128

1. The model was ballasted initially to a net positive buoyancy condition corresponding to approximately 250 pounds full-scale.
2. With this weight condition, the static roll and pitch trims were set to angles of 0 degrees by adjustment of the lateral and longitudinal ballast locations.
3. A known static rolling moment was applied about the centroid of the hull envelope, and the resulting angle of roll was measured. Using the relationship,[1]

$$K = (Z_G \; W - Z_B \; B) \sin \phi \tag{1}$$

the center of total mass of the model was adjusted to coincide with that of the prototype.

4. The model then was oscillated freely in roll and pitch, and the resulting periods of oscillation were recorded. These data were used to determine the moments of inertia in roll and pitch from the relationships[2]

$$T_\phi \cong 2\pi \; [I_x - K_{\dot{p}})/(Z_G \; W - Z_B \; B)]^{1/2} \tag{2}$$

and

$$T_\theta \cong 2\pi \; [(I_y - M_{\dot{q}})/(Z_G \; W - Z_B \; B)]^{1/2} \tag{3}$$

The values for $K_{\dot{p}}$ and $M_{\dot{q}}$ in Equations (2) and (3) were obtained from experimental data contained in Reference 3.

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[1]Imlay, Frederick H., "Complete Expressions for the Gravitational and Buoyancy Force Terms in the Equations of Motion of a Submerged Body," David Taylor Model Basin Report 1845 (Jun 1964).
A complete listing of References is given on page 43.

[2]Gertler, Morton and Grant R. Hagen, "Standard Equations of Motion for Submarine Simulation," Naval Ship Research and Development Center Report 2510 (Jun 1967).

[3]Young, D.C., "Model Investigation of the Stability and Control Characteristics of the Contract Design for the Deep Submergence Rescue Vehicle," Naval Ship Research and Development Center Report 3030 (Apr 1969).

The moment of inertia in yaw, while not specifically determined, is assumed to be very near that in pitch. This assumption is considered valid since the vehicle is essentially axially symmetric and the center of total mass is near the axis.

MODEL 5200

Model 5200 was ballasted using similar procedures but with an initial net positive buoyancy corresponding to approximately 260 pounds full-scale. Provision was made to allow the buoyancy to be varied through a range from 260 to 2730 pounds full-scale. Level static roll and pitch trims were maintained for this buoyancy range.

Table 2 lists the ballast conditions and the inertial properties of the models and compares them to those of the prototype. Note that the inertial scaling was generally accurate except for the natural period of roll of Model 5128, where the techniques by which this model had been constructed limited the available moment of inertia in roll.

The effect on selected static and inertial parameters of variation in buoyancy for Model 5200 is shown in Figures 12 and 13.

EXPERIMENTAL EQUIPMENT AND INSTRUMENTATION

The towing equipment and instrumentation used in the experiments are described below.

MODEL 5128

In the interest of construction time and economy, a direct-wire instrumentation system was employed. Also, preliminary investigations of probable tensions,[3,4] as well as basic handling considerations, suggested that a fiber rope towline with an equivalent full-scale circumference of 5 to 8 inches would be a likely choice.

With the foregoing as a design rationale, model towlines of various lengths were assembled in model scale using the following scheme: Through a tubular 9/16-inch plastic jacket, a 5/32-inch wire rope strength member and twenty electrical conductors were inserted, and the ends of the jacket were sealed. This technique produced towlines of reasonable diameter and density which satisfied the experimental electrical and strength requirements.

Towing bridles were constructed of 7/16-inch-diameter double-braided nylon line, and a spreader bar was constructed from a length of 1.315-inch-outside-diameter aluminum tubing.

[4] Feldman, J.P., "Model Investigation of Stability and Control Characteristics of a Preliminary Design for the Deep Submergence Rescue Vessel (DSRV Scheme A)," David Taylor Model Basin Report 2249 (Jun 1966).

TABLE 2 – BALLAST CONDITIONS AND INERTIAL PROPERTIES FOR THE DSRV PROTOTYPE AND MODELS

Ballast Conditions	Prototype	Scaling Factor	Model 5128*	Model 5200*
Total weight including entrained water, pounds**	139,769	$\rho_p/\rho_m\ \lambda^3$	5,036	14.12
Buoyancy of hull envelope, pounds	140,019	$\rho_p/\rho_m\ \lambda^3$	5,045	14.15
Net positive buoyancy, pounds**	250–260	$\rho_p/\rho_m\ \lambda^3$	9	0.03
Longitudinal distance to center of total mass from forward perpendicular, feet	23.11	λ	7.70	1.086
Height of center of total mass above baseline, feet	3.76	λ	1.25	0.177
Vertical distance between centroid of hull envelope and center of total mass, feet	0.15	λ	0.05	0.007
Moment to roll 1 degree, foot-pounds	354.3	$\rho_p/\rho_m\ \lambda^4$	4.4	0.00185
Inertial Properties				
Moment of inertia in roll, slugs–square feet	37,800	$\rho_p/\rho_m\ \lambda^5$	56	0.007
Moment of inertia in pitch, slugs–square feet	452,000	$\rho_p/\rho_m\ \lambda^5$	1,834	0.115
Moment of inertia in yaw, slugs–square feet	450,000	$\rho_p/\rho_m\ \lambda^5$	----	----
Natural submerged period of oscillation in roll, seconds	11.0	$\lambda^{1/2}$	5.0	2.2
Natural submerged period of oscillation in pitch, seconds	41.4	$\lambda^{1/2}$	24.0	9.0

*Experimentally determined.

**Reference condition for inertial experiments.

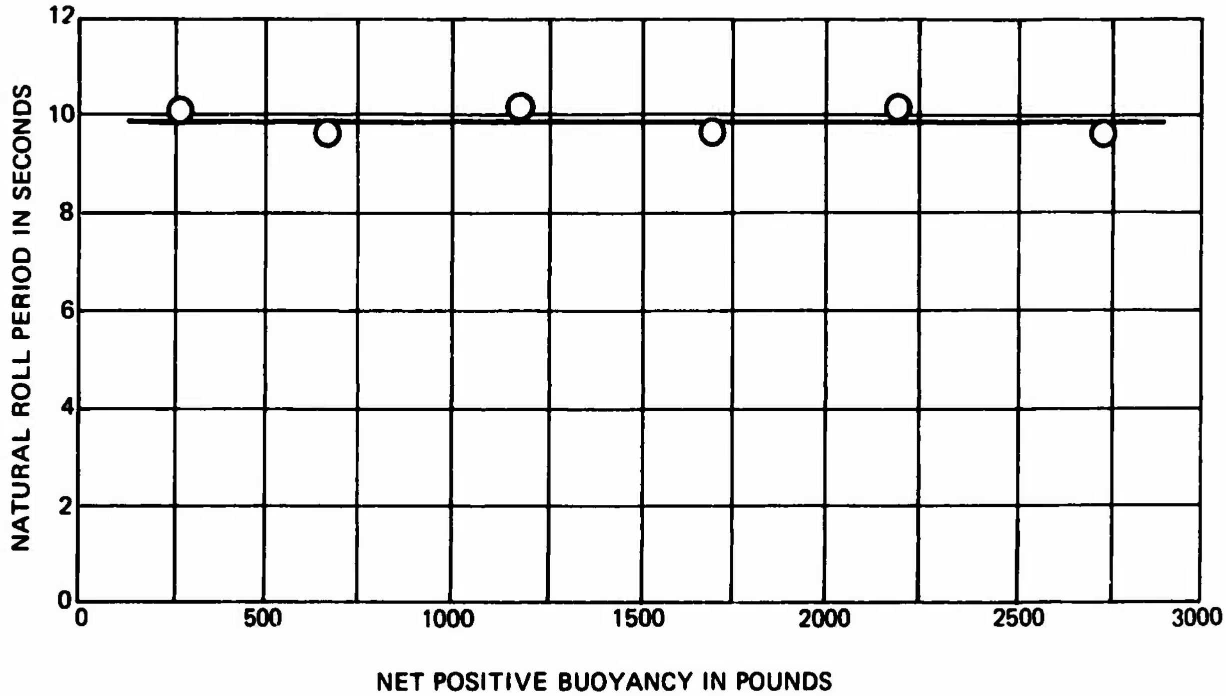

Figure 12 – Natural Roll Period as a Function of Buoyancy for the Full-Scale Vehicle as Represented by Model 5200

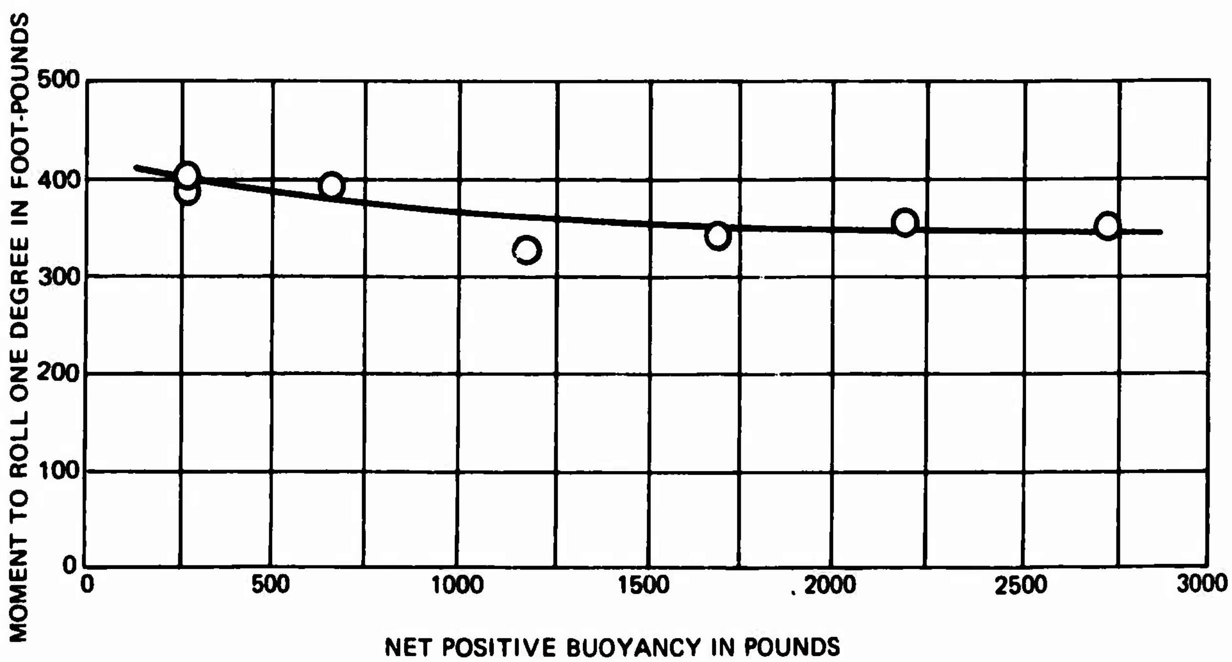

Figure 13 – Moment to Roll One Degree as a Function of Buoyancy for the Full-Scale Vehicle as Represented by Model 5200

The subsurface towing strut assembly that was used in these experiments has a tapered, approximately ogival section and may be varied in depth by means of an electrical hoist. The strut was designed to accept a maximum drag load of 3000 pounds and a maximum lateral load of 900 pounds.

Instrumentation located at the towing strut consisted of an angle potentiometer to measure vertical cable angle and a ring gauge dynamometer of 1200-pound-capacity to provide measurements of towing tension. The overall system accuracy for the angle potentiometer was ±1/2 degree; the ring dynamometer was accurate to ±6 pounds.

Instrumentation located within the model included the following:

1. A gyroscope platform to sense body attitude. This unit consisted of primary and back-up vertical-axis gyros each capable of measuring pitch and roll of the model to an overall accuracy of ±1/2 degree;
2. A yaw rate gyro, the signal of which when integrated yielded a yaw measurement accurate to ±1/2 degree over time periods shorter than 1 minute;
3. A feedback potentiometer (shown in Figures 5 and 6) to monitor deflection of the shroud by the remote rudder servo mechanism. This provided an accuracy of ±1/4 degree, but end play in the servo drive motor bearings, as well as positional stability of the shroud, limited accuracy to ±1/2 degree; and
4. A leak detection circuit for sensing water leakage in the pressure cans which housed the gyroscopes.

Speed measurements with an accuracy of ±0.01 knot were obtained with a magnetic pickup on the towing carriage. Analog data readout was provided by an eight-channel pen recorder.

MODEL 5200

The towline selected for Model 5200 was a low-density cable with an 0.087-inch-diameter and a nominal breaking strength of 100 pounds. The above-surface towing strut assembly used for experimentation with this model was fabricated from aluminum alloy and designed to accept a maximum drag or lateral load of 10 pounds. The strut could be varied in towing height from 0 to approximately 3 feet above the surface. Speed was measured by the same means as that used during investigations with Model 5128.

EXPERIMENTAL PROCEDURES

The experiments were carried out primarily with Model 5128, in both the high-speed and deep-water basins with a vehicle net positive buoyancy corresponding to 250 pounds and towlines corresponding to nominal lengths of 45 and 100 feet. Subsequent experiments

were conducted with Model 5200 in the high-speed basin to investigate the effects on stability of increased towline length and greater amounts of net positive buoyancy. The smaller scale model was selected for the latter experiments to eliminate the danger of collision with the basin floor and walls and to facilitate rapid ballast changes.

MODEL 5128

Steady-state attitudes and forces, as well as stability characteristics, were investigated over a simulated full-scale speed range from 5 through 15 knots for various towpoints and depths of tow. Changes in towing depth were accomplished by variations in the depth of the towing strut.

The greater portion of the experimentation was carried out using the arrangement shown in Figure 14 with a simulated full-scale towline length of approximately 45 feet, but stability and response characteristics were confirmed with a towline length corresponding to 100 feet.

Specific bridle geometry was varied to suit the various towpoints. A simple bridle arrangement was used when towing from the lifting eyes. With towpoints below the lifting eyes, however, a spreader bar was employed to prevent the bridle legs from coming into contact with the hull of the model. The bridle configurations are shown in Figure 15.

Experiments were conducted primarily with the open bottom of the mating skirt closed with a circular aluminum plate. However, a series of runs was made through the speed range to investigate the effect of removing this plate.

Each towing run was initiated with the model surfaced and oriented in the towing direction and the yaw signal set to zero. The carriage then was accelerated to the desired towing speed. After the initial transient behavior had damped out, an approximately square pulse was input to the rudder on most runs and the resulting behavior was observed. The carriage then was decelerated to allow the model to be secured. During most runs, the towing carriage was initially accelerated at a rate of approximately 0.6 foot/second/second. To investigate the effect of varying this initial acceleration, one run also was made with an acceleration of approximately 0.1 foot/second/second.

MODEL 5200

The stability of Model 5200 was investigated through a range of net positive buoyancies corresponding to 130 to 2730 pounds full-scale and a range of speeds up to 15 knots full-scale. All experiments with Model 5200 were conducted using the forward lifting eyes as towpoints and a simple bridle with leg lengths corresponding to 8 feet. Bridle geometry is shown in Figure 15b. The towing strut was set at a simulated height of 9.8 feet above the water surface. For comparative purposes, the stability for each model configuration was examined using nominal towline lengths corresponding to 50 feet, 100 feet, 300 feet, and 400 feet full-scale.

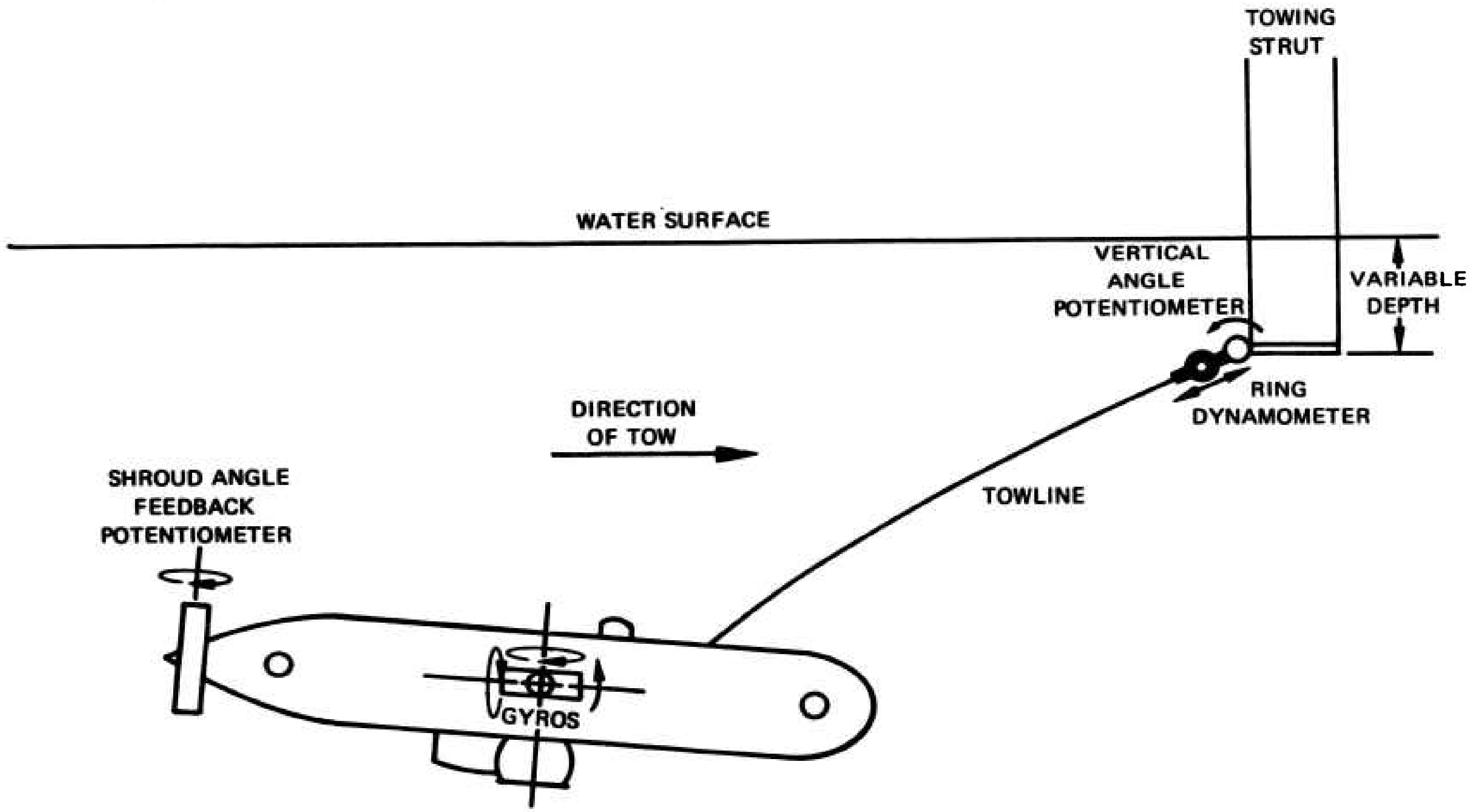

Figure 14 – Schematic Diagram of Model 5128 Towing Arrangement

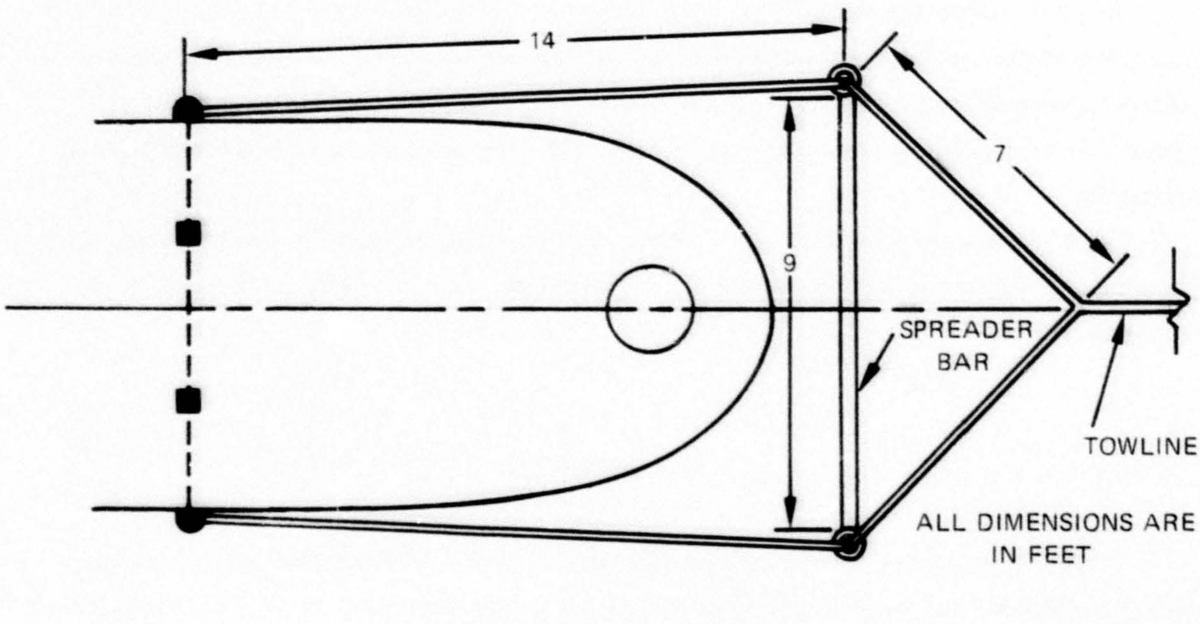

Figure 15a – Bridle with Spreader Bar

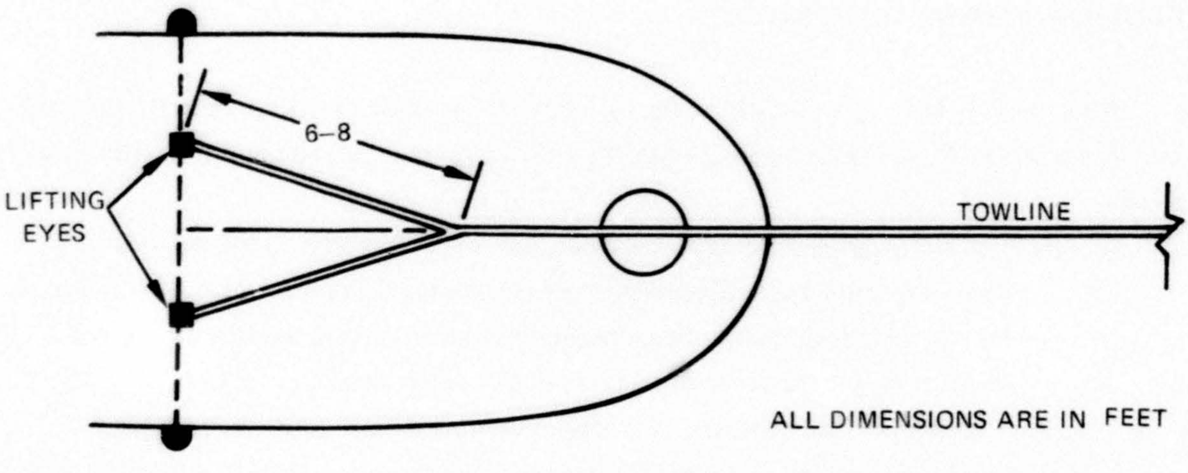

Figure 15b – Simple Bridle

Figure 15 – Top View of Towing Bridle Geometries Showing Principal Full-Scale Dimensions

Since a locked tail shroud was specified as an operational restriction, the great bulk of experimentation was carried out employing such a configuration. However, a small additional series of experiments with the model ballasted to a condition simulating approximately 1000 pounds net positive buoyancy was performed with the shroud and its supporting struts removed.

During each experimental run, stability was investigated both by observing the spontaneous behavior of the model and by observing the behavior after manually disturbing the model to an angle of yaw.

RESULTS

A sketch indicating the general towing configuration and defining the data variables is shown in Figure 16. Unless otherwise noted, all results presented in the following section represent data obtained using Model 5128.

GENERAL TOWING PERFORMANCE

Both models were dynamically stable and extremely steady in deep water submerged tow under all conditions investigated, with the following two exceptions noted with Model 5200:

1. For net positive buoyancies greater than approximately 2200 pounds full-scale, the model lateral stability was somewhat degraded. This was indicated by irregular rolling and kiting oscillations of moderate amplitude. These motions appeared to be independent of towing speed.
2. With the shroud removed, the model exhibited large and erratic lateral oscillations which increased in amplitude with towing speed. At speeds above 9 knots full-scale, the model frequently broached the surface.

A substantial transient in pitch of up to −25 degrees occurred as the models initially submerged, but this was well damped over the speed range for depths of tow greater than about 27 feet full-scale. This is illustrated in Figure 17 for the case of towing from the forward lifting eyes with a vehicle net positive buoyancy corresponding to 250 pounds. An approximate depth trace for this condition is shown in Figure 18. This trace indicates that there was very little depth overshoot. A very low acceleration appeared to have little effect on the initial diving transient.

Response of Model 5128 to the rudder servo was smooth and controllable making it possible to finely adjust lateral running position by this means. Of greater interest was the

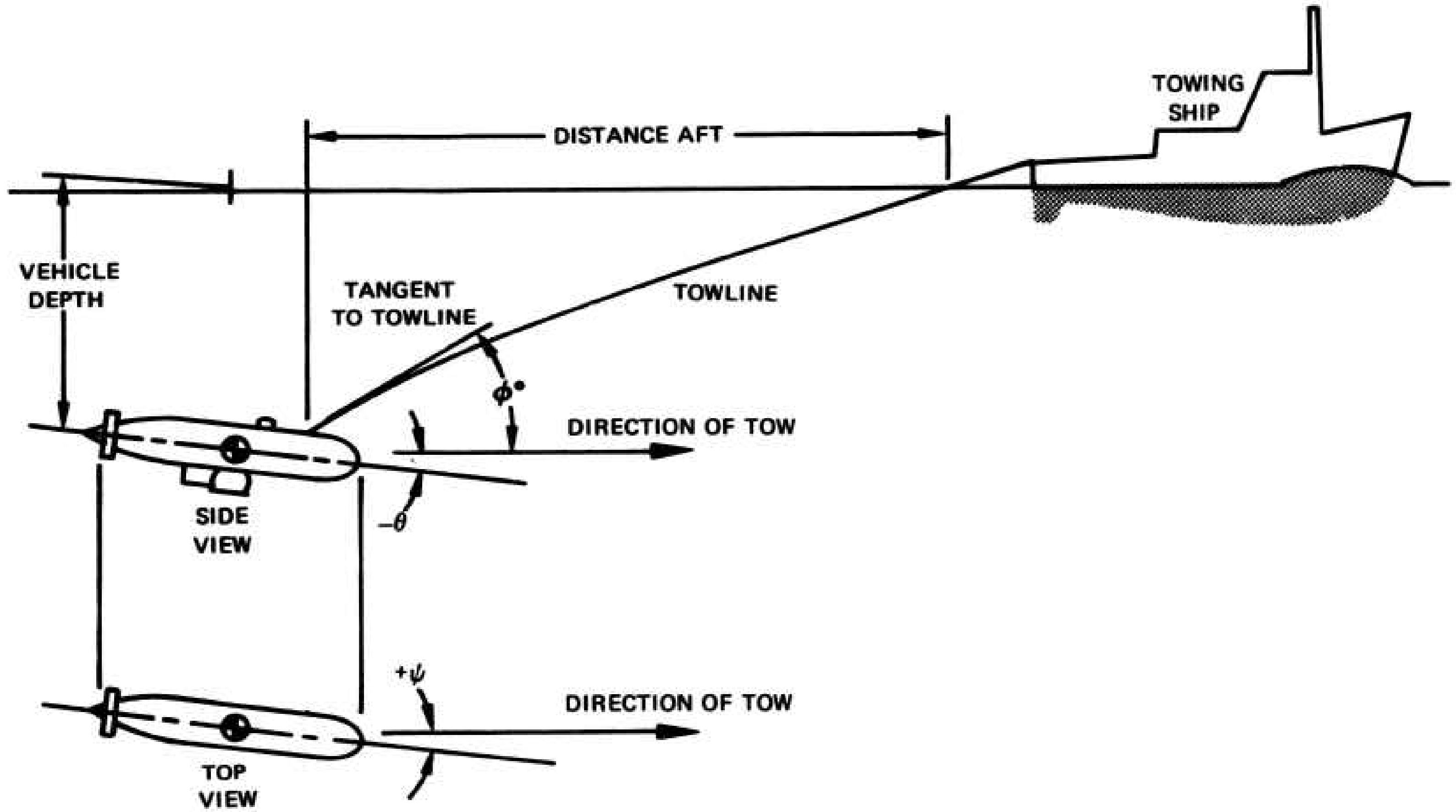

Figure 16 – Sketch of Simulated General Towing Configuration Defining Data Variables

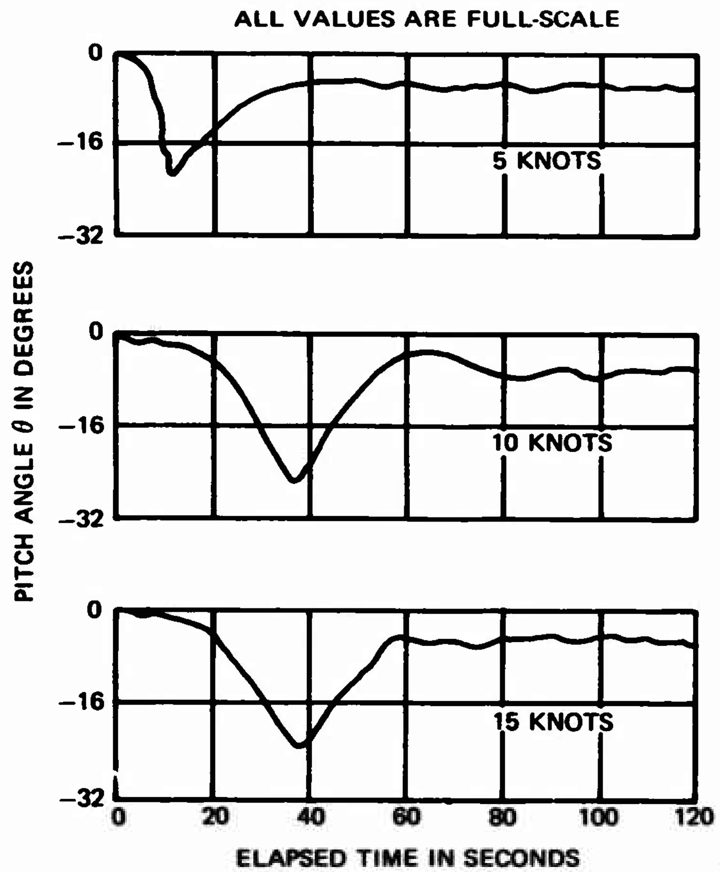

Figure 17 – Vehicle Response in Pitch During Initial Submergence as a Function of Time After Initial Tension Rise in Towline

(Towpoint: Lifting Eyes; Towline Length: 100 feet; Buoyancy: 250 pounds positive)

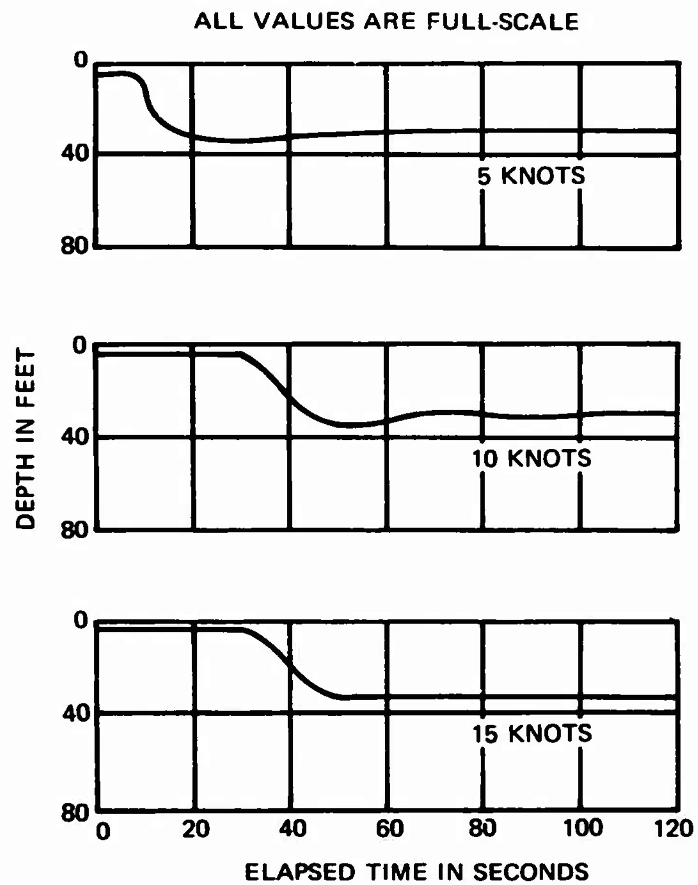

Figure 18 – Approximate Towing Depth of Centroid of Hull During Initial Submergence as a Function of Time After Initial Tension Rise in Towline

(Towpoint: Lifting Eyes; Towline Length: 100 feet; Buoyancy: 250 pounds positive)

excellent damping in yaw demonstrated by the response to a simple rudder pulse. This is indicated by the yaw traces shown in Figures 19 and 20 for two lengths of towline. These figures demonstrate also that a longer yaw period is associated with the longer towlines.

Response in yaw was accompanied, because of towpoint height, by response in roll. The resulting roll was substantial (up to 20 degrees in the case of towing from the lifting eyes), especially for large rudder pulses at high speed, but the motion was directly coupled and proportional to the rolling moment applied by the towline as the model yawed and trailed to the side. The natural roll dynamics of the model had no observable influence on either the response or the stability. This suggests that the inability to scale the moment of inertia in roll (see Table 2) did not significantly influence the model response or stability.

INFLUENCE OF THE FREE-SURFACE

The free-surface had a substantial effect on both the steady-state and the dynamical towing characteristics. The effect of the free-surface proximity on the steady-state pitch attitude with a vehicle net positive buoyancy of 250 pounds is shown in Figure 21. The general effect of Froude number on the damping of the initial dive transient in pitch during near-surface towing is illustrated in Figure 22. In this figure, the values of the damping ratio δ, (equal to the ratio of the damping constant to the critical damping constant) were determined from the expression,[5]

$$\delta = \frac{\ell_n \left(A_{n+1}/A_n\right)}{2\pi} \tag{4}$$

where A_{n+1}/A_n is the ratio of the amplitudes of two consecutive oscillations. Although indicating specifically the effects of the free-surface on the vehicle towing performance for a nominal steady-state towing depth of 23 feet full-scale when using the capture arms as the towpoint, this figure is generally indicative of the effects observed for all towpoints examined at depths of tow less than 27 feet. As indicated in the previous sub-section and shown in Figures 17 and 18, at increased towing depths these transient motions were highly damped.

[5] Rauscher, Manfred, *Introduction to Aeronautical Dynamics*, John Wiley and Sons, New York, 1953.

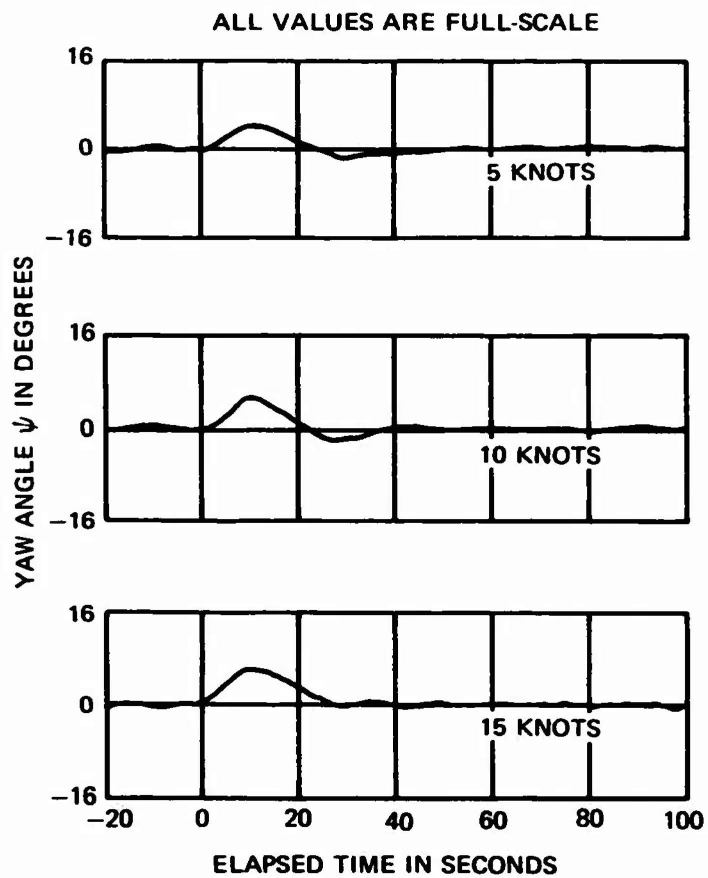

Figure 19 – Vehicle Response in Yaw to Rudder Pulse as a Function of Time After Start of Pulse

(Towpoint: Lifting Eyes; Towline Length: 45 feet; Buoyancy: 250 pounds positive)

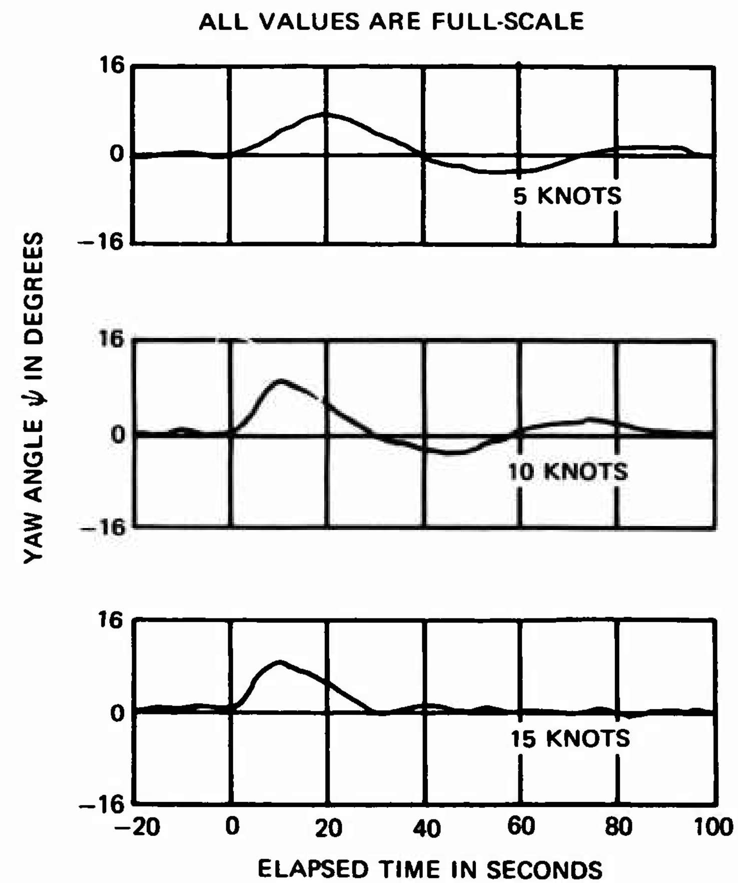

Figure 20 – Vehicle Response in Yaw to Rudder Pulse as a Function of Time After Start of Pulse

(Towpoint: Lifting Eyes; Towline Length: 100 feet; Buoyancy: 250 pounds positive)

ALL VALUES ARE FULL-SCALE

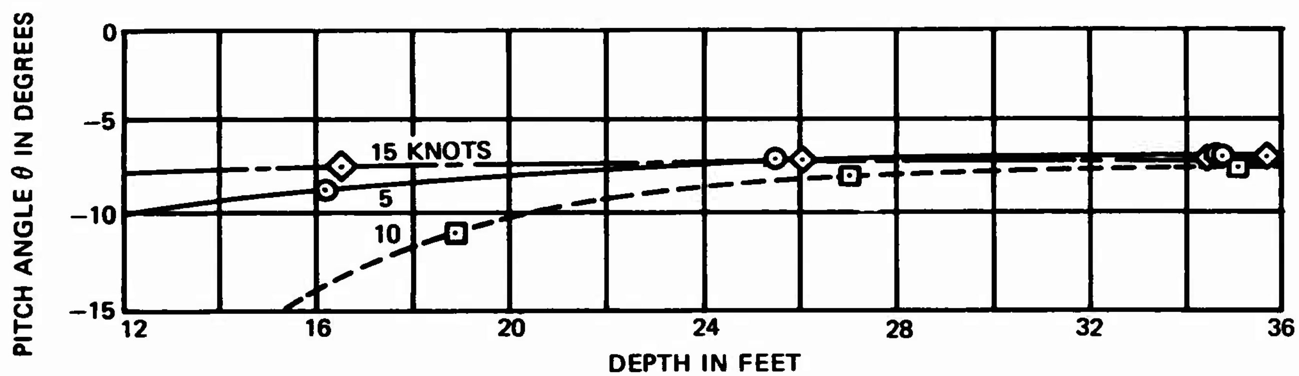

Figure 21a – Towpoint at Lifting Eyes

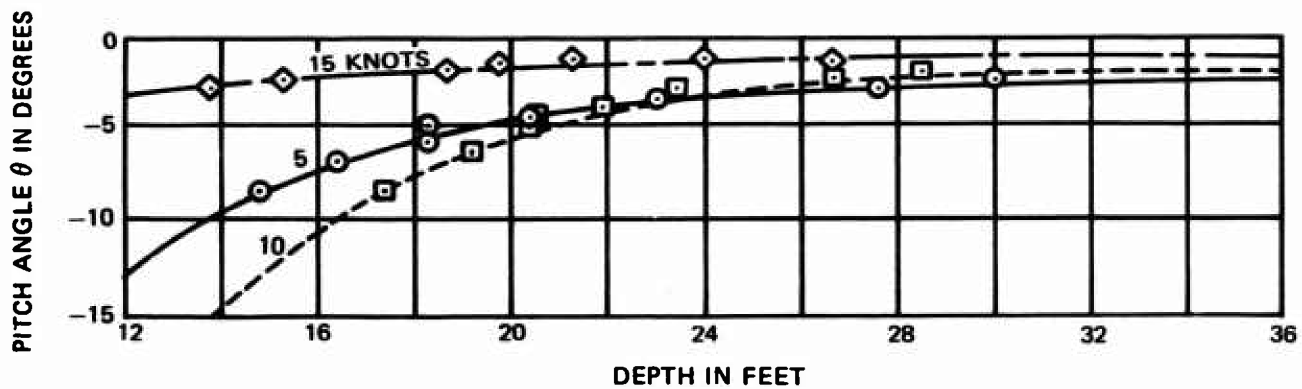

Figure 21b – Towpoint at Capture Arms

Figure 21 – Vehicle Pitch Angle as a Function of Towing Depth to Centroid of Hull for Various Speeds

(Buoyancy: 250 pounds positive)

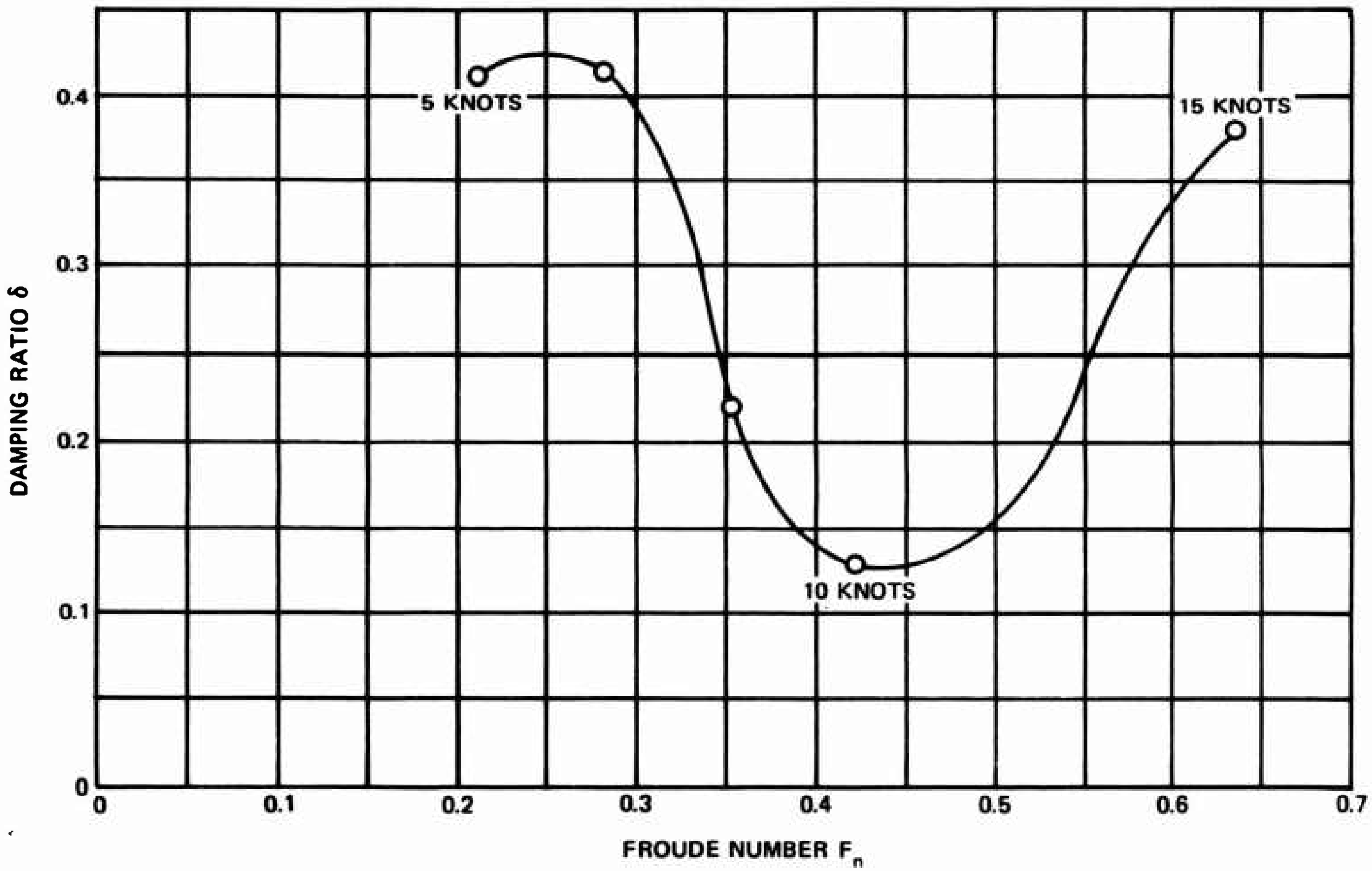

Figure 22 – Damping Ratio in Pitch After Initial Submergence as a Function of Froude Number

(Towpoint: Capture Arms; Nominal Towing Depth to Centroid of Hull: 23 feet; Buoyancy: 250 pounds positive)

INFLUENCE OF THE BOTTOM

Water depths shallower than some critical value between 50 and 65 feet were found to have a serious effect on the damping of the initial diving transients. Figure 23 compares transient depth data obtained in simulated water depths of 48 and 66 feet full-scale using the capture arms as the vehicle towpoint. In the shallower water, the motions are at best poorly damped and show distinct signs of diverging with higher speed.

VEHICLE ATTITUDES AND FORCES

The variations obtained in deeply-submerged equilibrium pitch attitude, towline angle, and tension for the vehicle with a net positive buoyancy corresponding to 250 pounds are shown in Figures 24a, 24b, and 24c, respectively. In these figures the symbols represent the data obtained in free tow, the vehicle towline angles and tensions having been predicted using the towline angles and tensions at the towing strut by the theory of Pode[6] with the aid of machine computations.[7] In these figures, longitudinal body forces have been corrected for Reynolds number effects using standard reduction techniques with a correlation allowance coefficient of 0.0006 being applied. For comparative purposes these figures also present curves representing values calculated using data obtained with Model 5128 on the NSRDC Planar-Motion Mechanism.[3] These model data were used to calculate equilibrium pitch attitudes and forces for various towpoint locations and speeds by balancing the forces and moments produced by the towline with those produced by the body. Complete gravitational and buoyancy force effects were included in making these calculations. Inspection of Figure 24b indicates that a considerable variation in towline angle at the vehicle (which reflects the lift/drag ratio) is available simply by adjusting the height of the towpoint.

Calculated values of pitch attitude, towline angle and tension at the vehicle plotted as functions of speed for various vehicle buoyancy conditions when towed from the forward lifting eyes are presented in Figures 25, 26, and 27, respectively. These values also were calculated using data from Reference 3 as described above. These curves indicate that the buoyancy condition has a significant effect on steady towing performance.

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[6]Pode, L., "Tables for Computing the Equilibrium Configuration of a Flexible Cable in a Uniform Stream," David Taylor Model Basin Report 687 (Mar 1951).

[7]Cuthill, E.H., "A FORTRAN IV Program for the Calculation of the Equilibrium Configuration of a Flexible Cable in a Uniform Stream," Naval Ship Research and Development Center Report 2531 (Feb 1968).

ALL VALUES ARE FULL-SCALE

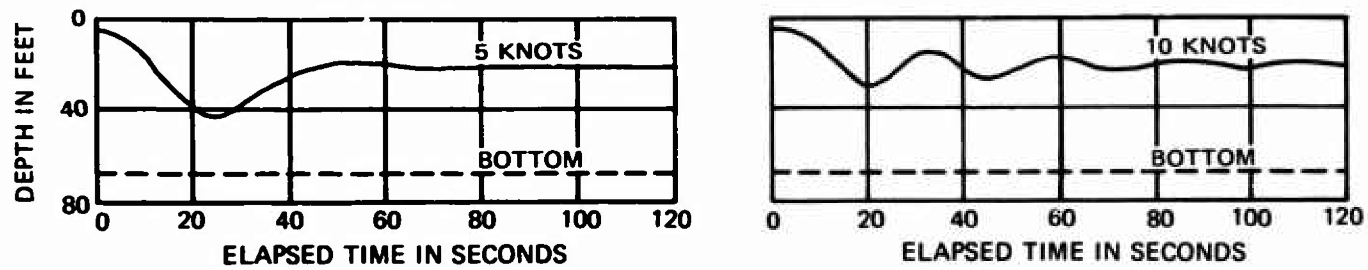

Figure 23a – Water Depth: 66 Feet

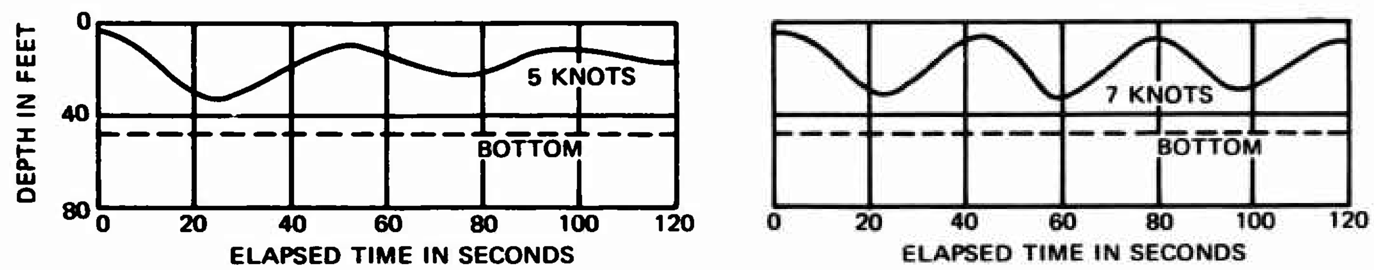

Figure 23b – Water Depth: 48 Feet

Figure 23 – Approximate Towing Depth to Centroid of Hull as a Function of Time After Initial Submergence for Two Depths of Water

(Towpoint: Capture Arms; Towline Length: 45 feet; Buoyancy: 250 pounds positive)

Figure 24 – Deeply-Submerged Vehicle Pitch Angle, Towline Angle, and Tension as Functions of Towpoint Height Above Centerline on Forward Hard Ring for Various Speeds

(Buoyancy: 250 pounds positive)

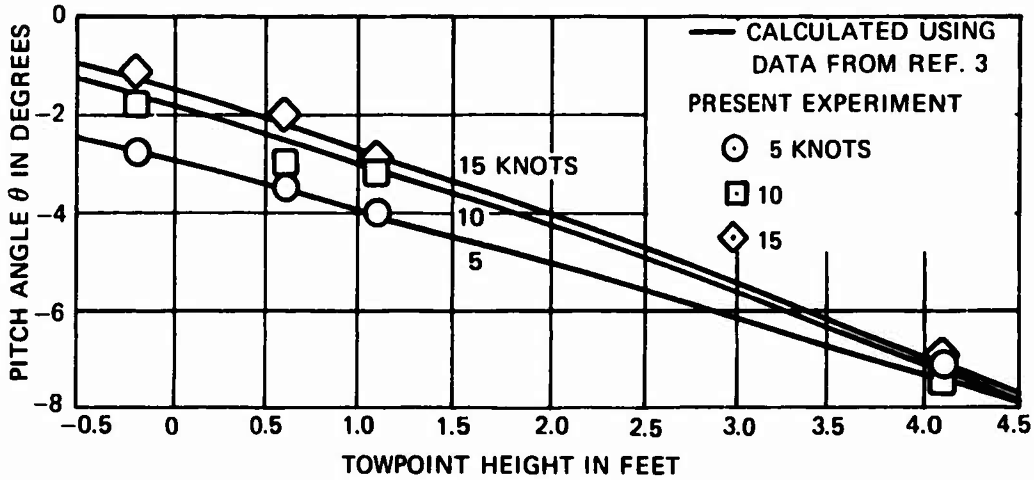

Figure 24a – Vehicle Pitch Angle

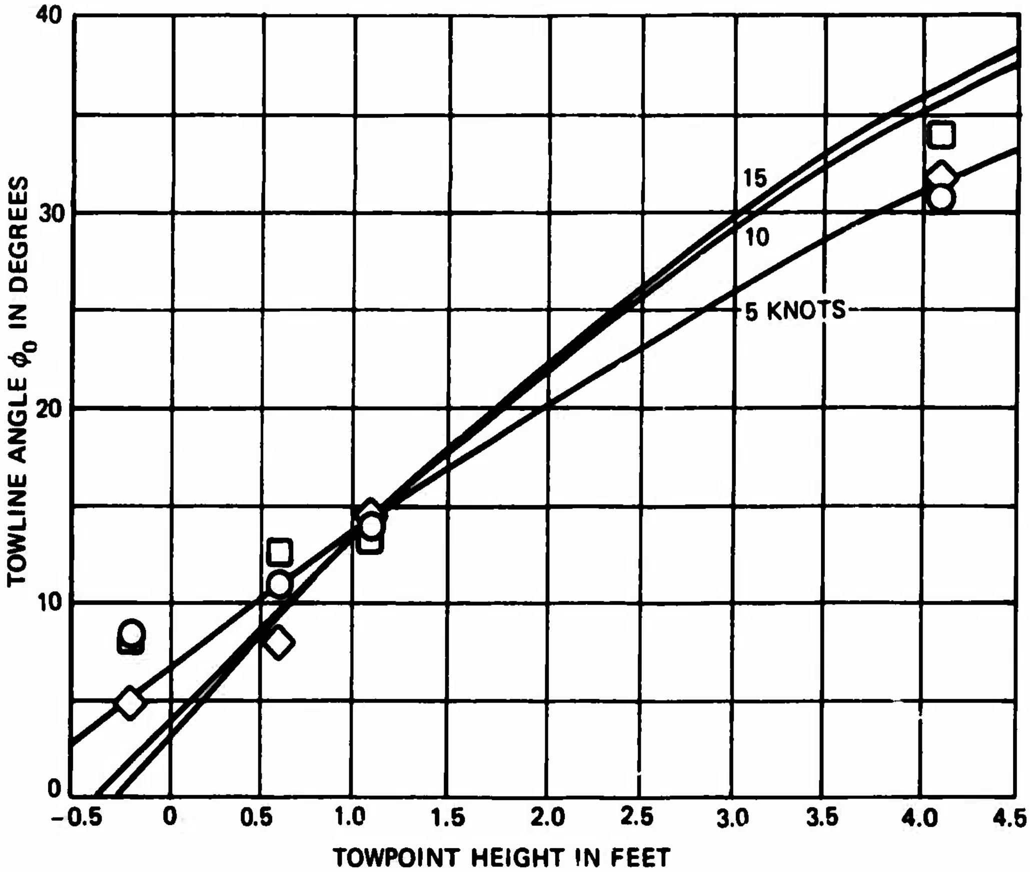

Figure 24b – Cable Angle at Vehicle

Figure 24 (Continued)

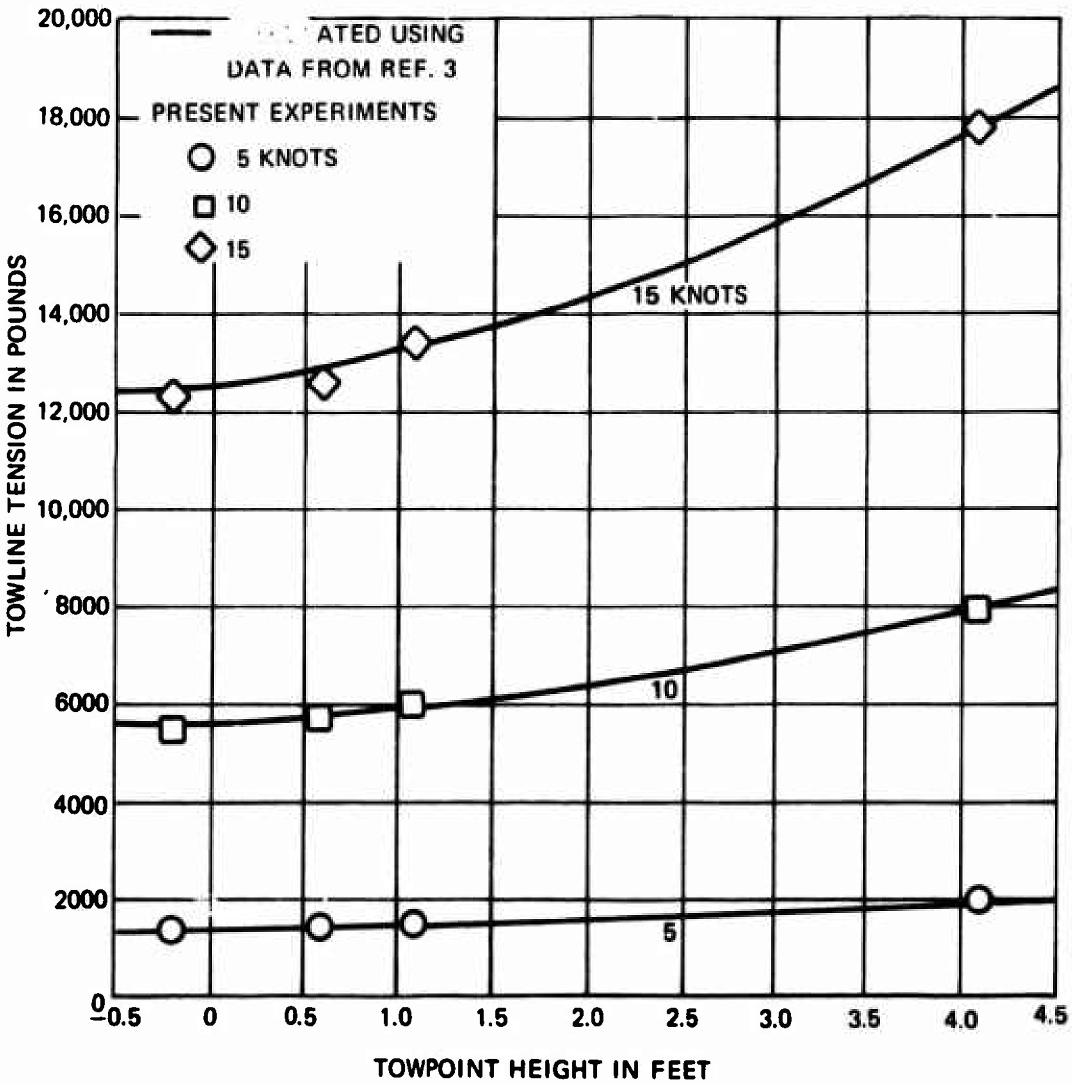

Figure 24c – Towline Tension at Vehicle

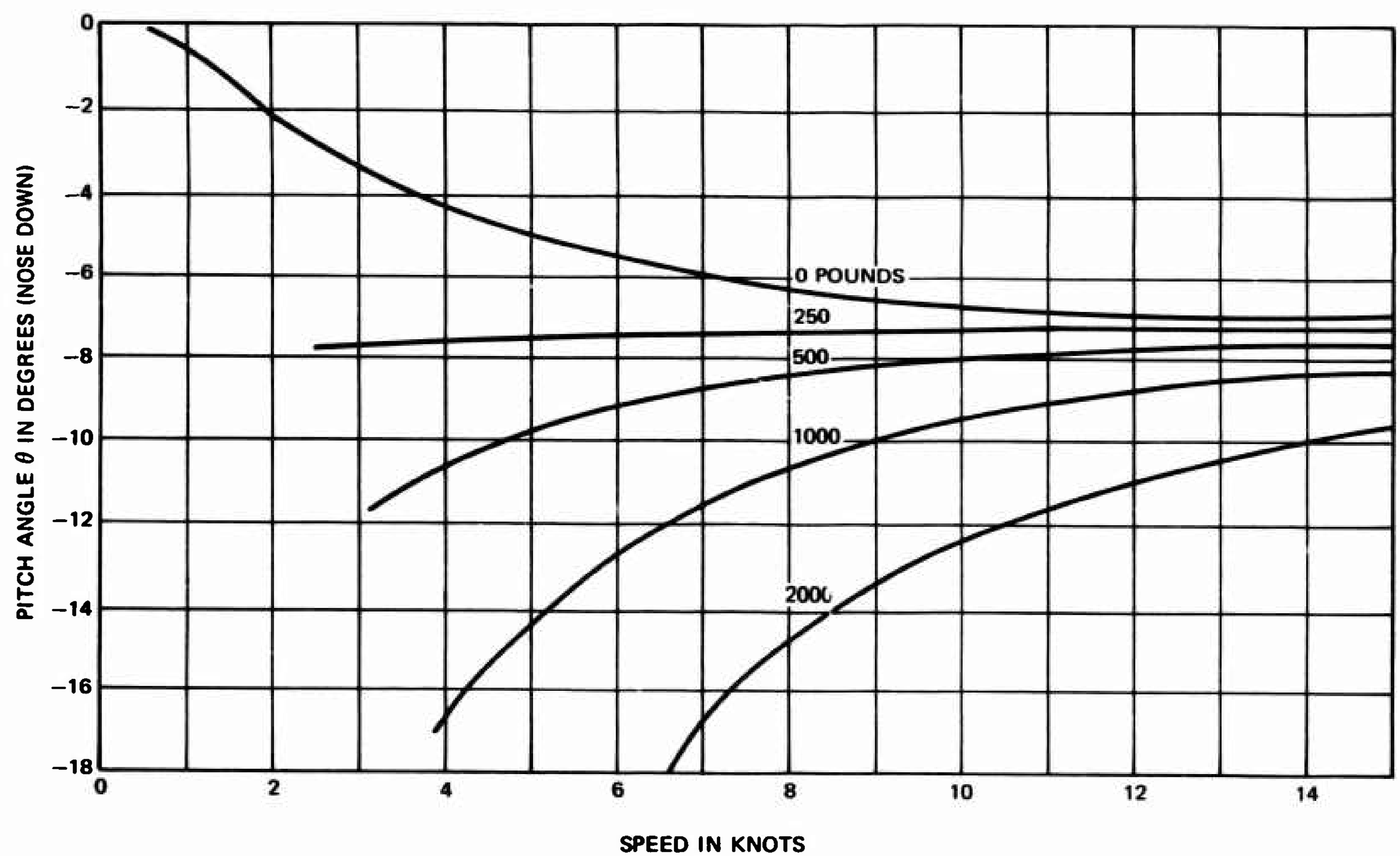

Figure 25 – Predicted Vehicle Pitch Angle as a Function of Towing Speed for Various Values of Vehicle Net Positive Buoyancy Using the Lifting-Eye Towpoint

(Calculated using data from Reference 3)

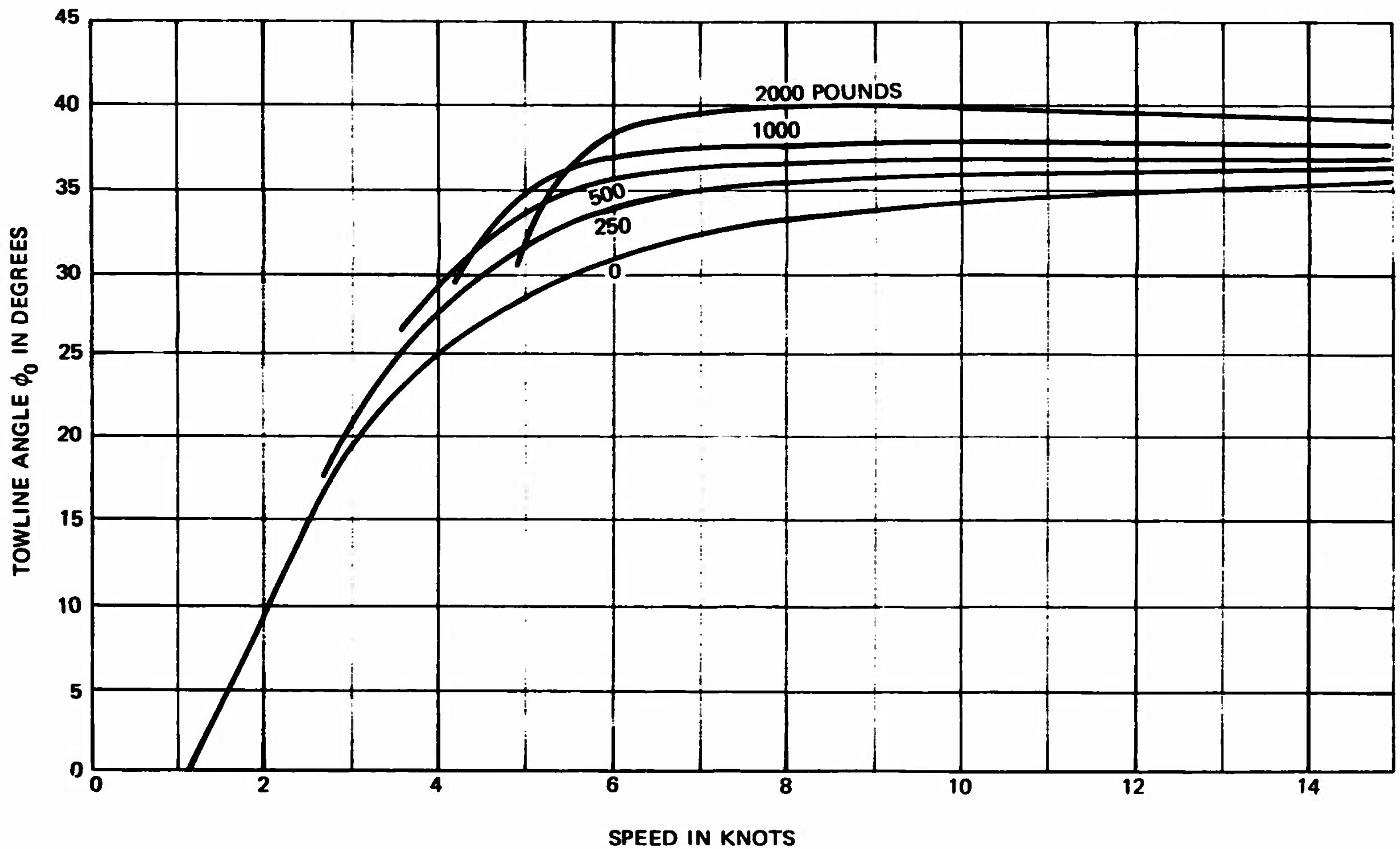

Figure 26 – Predicted Towline Angle at Vehicle as a Function of Towing Speed for Various Values of Vehicle Net Positive Buoyancy Using the Lifting-Eye Towpoint

(Calculated using data from Reference 3)

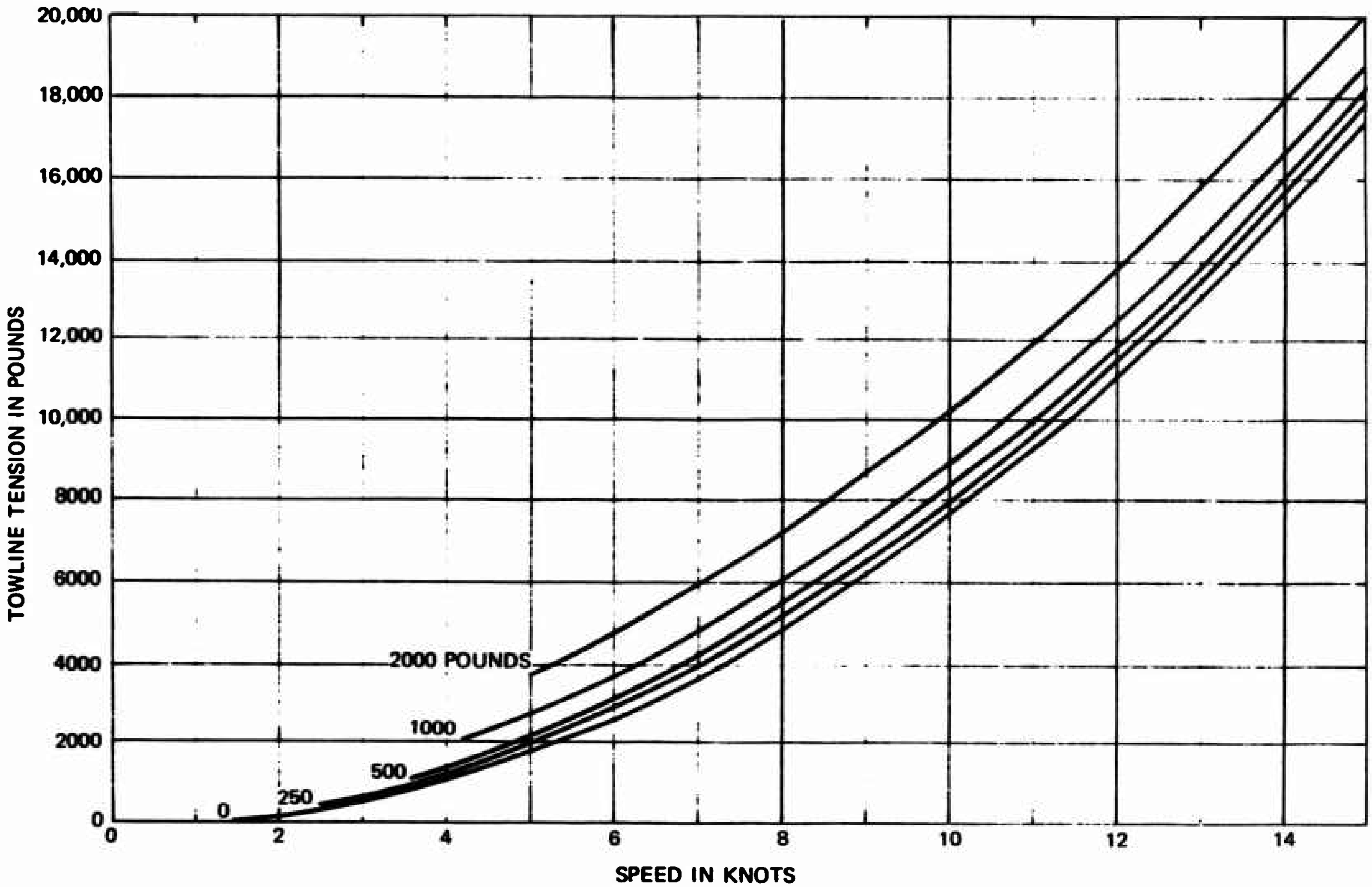

Figure 27 – Predicted Towing Tension at Vehicle as a Function of Towline Speed for Various Values of Vehicle Net Positive Buoyancy Using the Lifting-Eye Towpoint

(Calculated using data from Reference 3)

EFFECT OF MATING SKIRT CLOSURE PLATE

There was no discernable effect on towing performance due to removal of the mating skirt closure plate which was in place during most of the experimentation.

PREDICTIONS OF TYPICAL TOWING CONFIGURATIONS

To obtain an indication of towing depth with long towline lengths, cable configurations were calculated[6,7] using an assumed neutrally buoyant, 2.0-inch diameter towline having a normal drag coefficient of 1.7 based on frontal area. Input body cable angles and tensions from Figures 26 and 27 were used in these calculations. Figure 28 shows the predicted towing configurations at 15 knots for a vehicle net positive buoyancy of 1000 pounds. Figure 29 indicates the influence of towing speed on the 600-foot towline configuration. These figures reflect the effects of towline stretch assuming a double-braided nylon/polypropylene rope towline. Figure 28 indicates that, for the vehicle buoyancy condition considered here, a towing depth of 100 feet will be achieved with a submerged towline length slightly greater than 200 feet. With 400 feet of submerged towline, the vehicle will tow at a depth of approximately 150 feet. The steady-towing tensions developed under these conditions are shown in Figure 30. For a 2.0-inch diameter nylon/polypropylene towline with an approximate strength of 92,000 pounds, the tensions produced under steady towing conditions are well within the recommended normal working loads.

In the event that vehicle buoyancy conditions other than 1000 pounds positive are utilized, the maximum towing depths for a given towline length will change somewhat. Figure 31 illustrates this effect for two additional buoyancy conditions.

Towline diameter also influences towing depth. This is illustrated in Figure 32 for towlines ranging from 2.0 inches to 4.0 inches in diameter.

CONCLUSIONS

1. The full-scale vehicle will be stable in deep water submerged tow when towed from either the forward lifting eyes or the forward ASR capture arms with net buoyancies from 130 to 2000 pounds positive. The shroud ring must be locked in place.

2. The vehicle should be towed at a submergence of at least 30 feet (centroid running depth) to be substantially out of the effects of the undisturbed free-surface.

3. A safe, stable submerged tow *cannot* be achieved in water that is less than 65 feet deep.

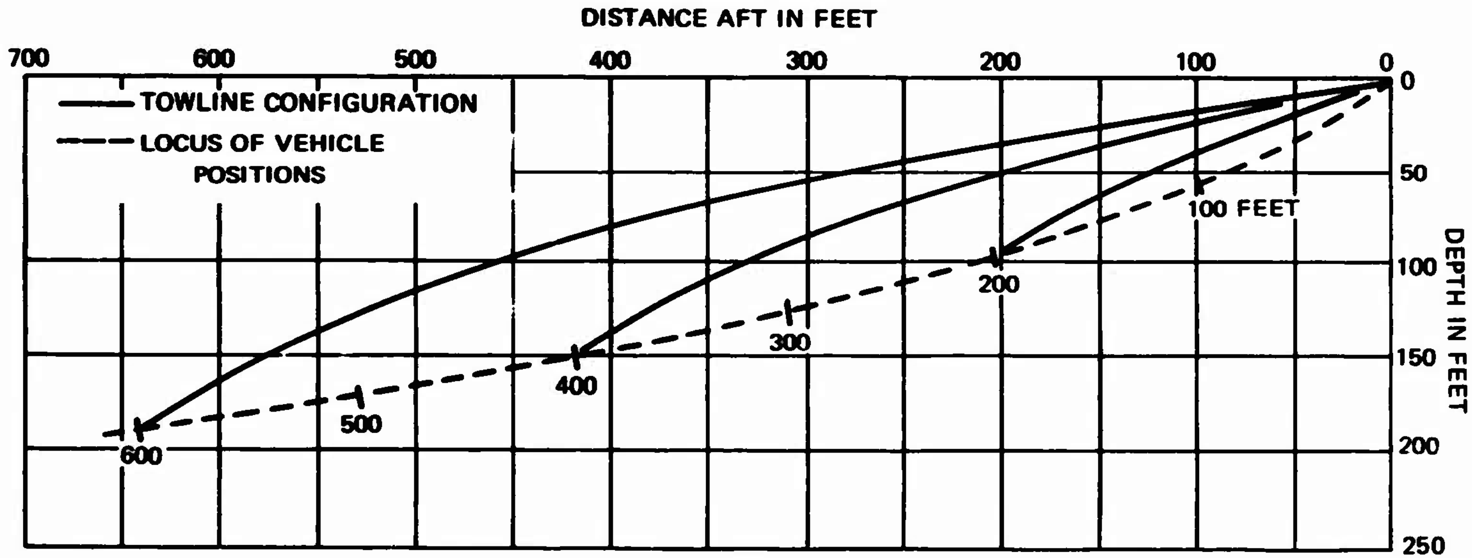

Figure 28 – Predicted Towline Configurations at 15 Knots for Various Unstretched Lengths of 2.0-Inch-Diameter Towline

(Vehicle Buoyancy: 1000 pounds positive; Towpoint: Lifting Eyes)

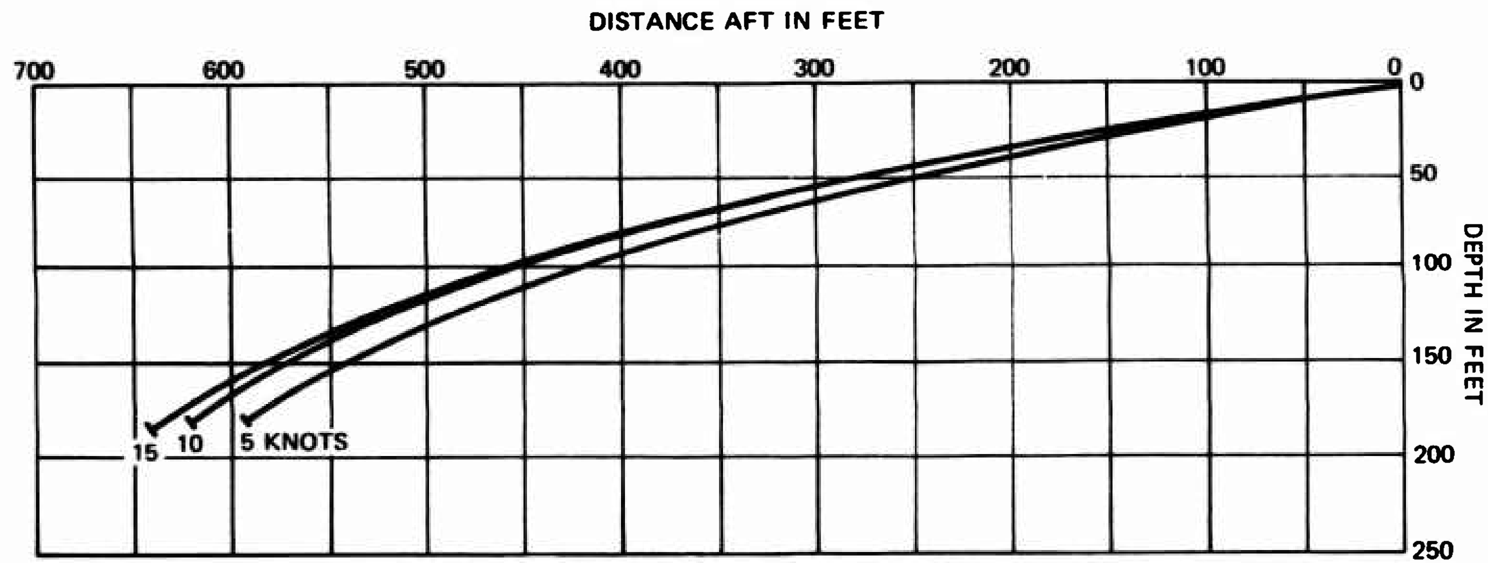

Figure 29 – Predicted Towline Configurations at Various Speeds for a 600-Foot-Unstretched-Length of 2.0-Inch-Diameter Towline

(Vehicle Buoyancy: 1000 pounds positive; Towpoint: Lifting Eyes)

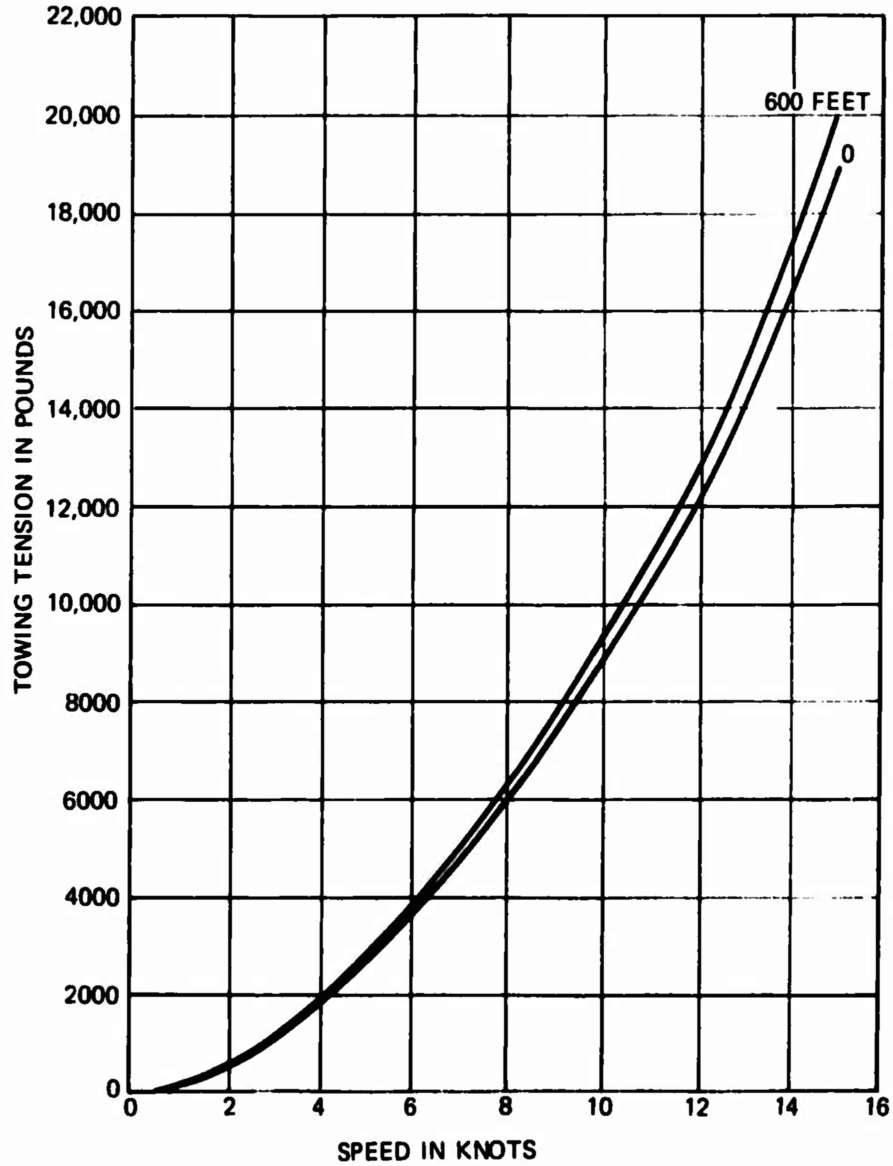

Figure 30 – Towline Tension at the Vehicle and at the Towing Ship as a Function of Speed for a 600-Foot-Unstretched-Length of 2.0-Inch-Diameter Towline

(Vehicle Buoyancy: 1000 pounds positive; Towpoint: Lifting Eyes)

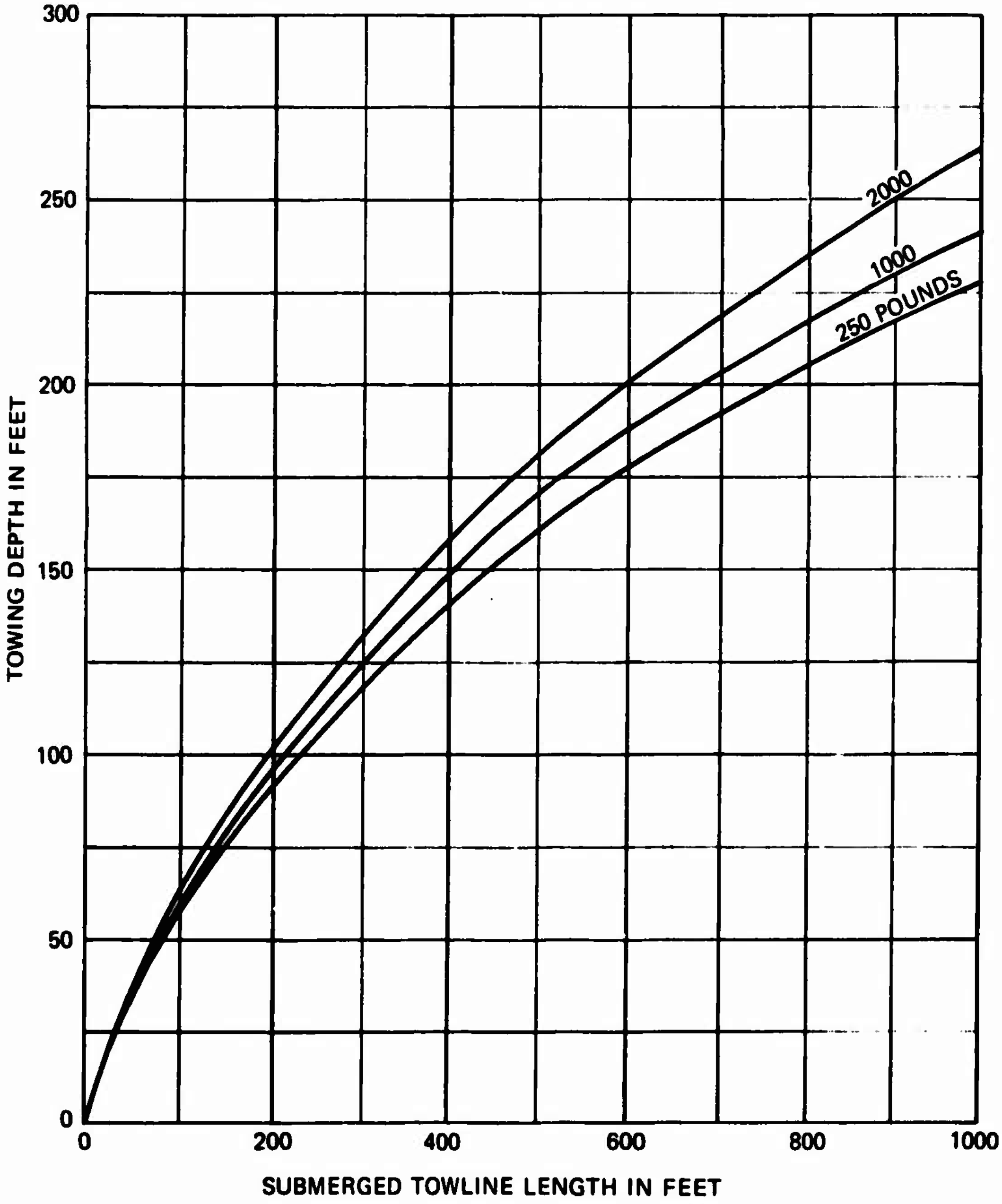

Figure 31 – Predicted Maximum Towing Depth Using a 2.0-Inch-Diameter Towline as a Function of Unstretched Submerged Towline Length for Various Values of Vehicle Net Positive Buoyancy

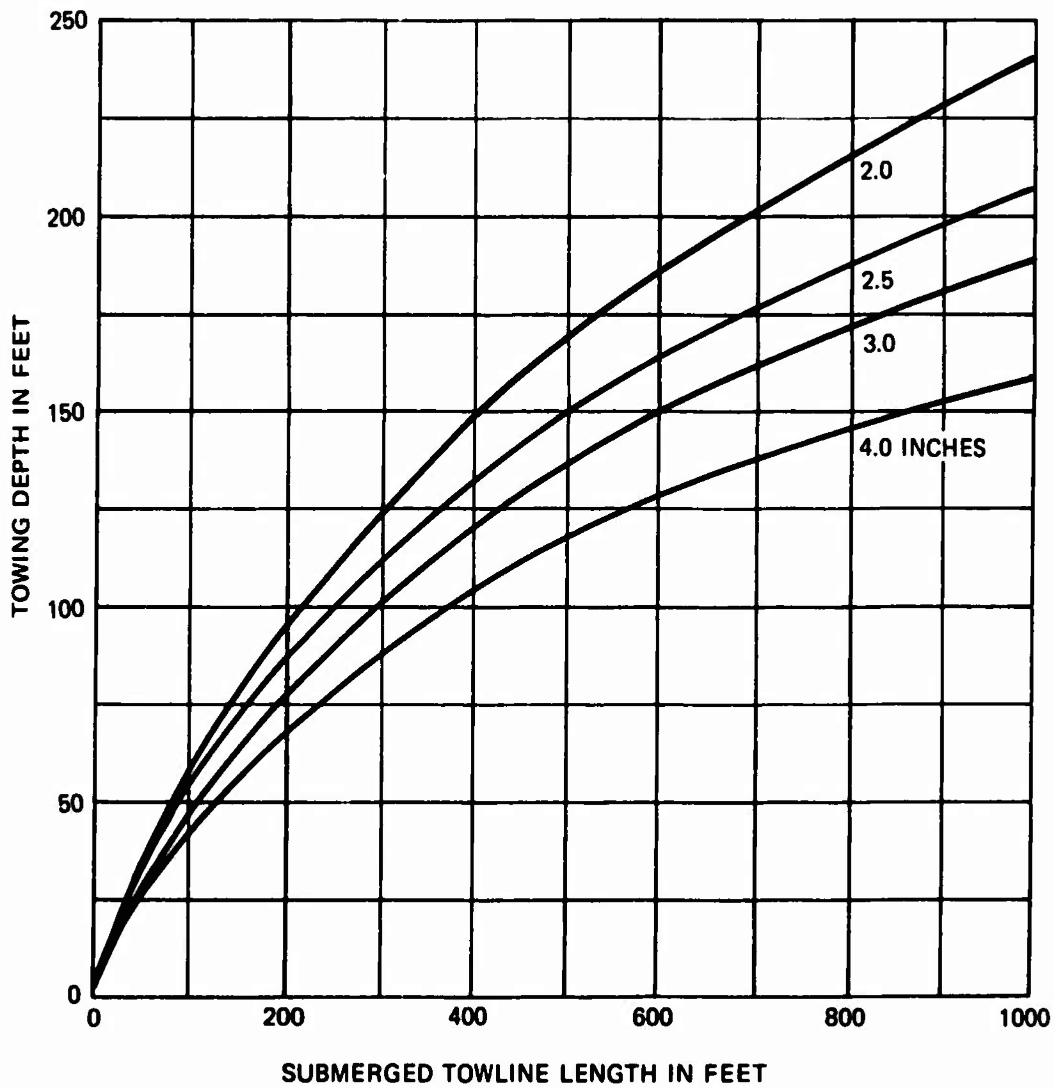

Figure 32 – Predicted Maximum Towing Depth with a Vehicle Net Positive Buoyancy of 1000 Pounds as a Function of Unstretched Submerged Towline Length for Various Towline Diameters

4. The vehicle will experience a substantial initial transient upon submerging, with initial pitch excursions of up to -25 degrees.

5. By far the most promising towpoint is that employing the forward lifting eyes. Using this towpoint, the vehicle alone (without additional appendages) will produce sufficient downforce to achieve a towing depth of 100 feet using slightly over 200 feet of towline. Also, a simple bridle geometry can be employed with this towpoint. The use of other towpoints would present some danger to the skin of the vehicle, even while employing a bridle with spreader bar.

6. A 2-inch diameter nylon towline with a breaking strength of 90,000 to 100,000 pounds would be adequate under steady towing conditions at 15 knots. However, to provide a substantial margin of safety in a seaway at 15 knots, a larger towline should be used.

ACKNOWLEDGMENTS

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